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ANALYZING THE RELATIONSHIP OF SOIL MOISTURE AND BIOPHYSICAL VARIABLES IN WET AND DRY SEASONS AT A RAINFED AND IRRIGATED FIELD IN EASTERN NEBRASKA

Eric Hunt
University of Nebraska-Lincoln, ehunt2@unl.edu

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Eric Daniel Hunt

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ANALYZING THE RELATIONSHIP OF SOIL MOISTURE AND BIOPHYSICAL VARIABLES IN WET AND DRY SEASONS AT A RAINFED AND IRRIGATED FIELD IN EASTERN NEBRASKA

Eric D. Hunt, Ph.D.

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Adviser: Brian D. Wardlow

Agriculture production, particularly of maize and soybeans, is a major component of Nebraska's economy and identity. However, agricultural production in Nebraska faces increasing challenges. One of the challenges is the potential for excessive groundwater depletion due to increased demand for food and fuel from irrigated Nebraska crops and increasing risks of water stress due to climate change. Therefore, it is has become essential for a deeper understanding of the soil-plant-atmosphere continuum to help producers make more informed management decisions. One of the most important variables is soil moisture. Soil moisture is an integral part of the hydrologic cycle and an essential component in understanding land-atmosphere interactions. Eight years of soil moisture and biophysical measurements from an irrigated and rainfed maize-soybean rotation, in growing seasons that ranged from abnormally dry and warm to unusually moist and cool, add to that understanding. It is shown that soil moisture is an excellent measure of the effectiveness of precipitation and that timing of precipitation can be as important as quantity. Dry spells occurred in most seasons in the study period, but the timing and duration of said dry spells were important. In seasons where adequate precipitation returned, measured evapotranspiration and gross primary productivity at the rainfed field increased to close to that of the irrigated field. Therefore, it is implied that stomatal conductance seemed to return to close to pre-dry spell levels and rainfed yields were not substantially reduced compared to the irrigated field. However, during a classic flash drought in the study period, prolonged soil moisture stress led to reduced stomatal conductance and significantly reduced maize yields. The flash drought case study not

only showed the importance of irrigation during a prolonged dry spell, it also showed the utility of using short-term drought indices for identifying water stress of a rainfed field.

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Service to others is always rewarding and I'm proud of my accomplishments in that realm.

In the late fall of 2011 I received a Facebook message from Sandra Jones asking if I would be interested in a job. I knew balancing work and a dissertation would be a challenge but it was a risk I had to take. On a warm Tuesday in March 2012, I began working for Atmospheric and Environmental Research, Inc. as a sub-contractor for Air Force Weather. Since that time I have also worked a bit with the United States Army Corps of Engineers Cold Regions Research Laboratory and more recently with the High Plains Regional Climate Center and have come to admire and respect my colleagues at NASA-GSFC, NCAR, NOAA, and the UK Met Office.

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CHAPTER 1: INTRODUCTION

1.0 Introduction

Agricultural production, particularly of maize and soybeans, is a major component of Nebraska's economy and identity. However, agricultural production in Nebraska faces increasing challenges, particularly in areas dependent on irrigation. One of the larger concerns is the potential for excessive groundwater depletion due to increased demand for food and fuel from Nebraska crops and increasing risks of water stress in growing seasons due to climate change. Given the importance of agricultural production to the state and the increasing environmental risks, it has become essential for a deeper understanding of the soil-plant-atmosphere continuum to help producers make more informed management decisions. One of the variables that producers are starting to use for decision-making is soil moisture. Soil moisture is an integral part of the hydrologic cycle and an essential component in our understanding of land-atmosphere interactions. Improved understanding of soil moisture response under major cash crops, such as maize and soybeans, and insights into the dynamics of the soil moisture-crop-atmosphere continuum are needed to help producers in irrigated regions make more informed decisions.

Contrary to popular belief, Nebraska has diverse terrain and ecosystems, ranging from predominant non-irrigated maize-soybean cropping systems in the far eastern corner to the semi-arid landscape of irrigated cropland and pasture in the western Panhandle. Precipitation gradients are sharp in the state and range from an average of just under 900 mm in the far southeast to an average of 300 mm in the western portion of the Nebraska. Thus, most areas in the far eastern corner of Nebraska, as is the case in Iowa and other states to the east, can regularly receive high-yielding crops under rainfed conditions, while crops grown west of the 100th meridian require irrigation for crops to achieve high yields.

Irrigated agriculture has provided consistently high-yielding crops for Nebraska producers and in a year when severe drought is affecting much of the Corn Belt, this can help to ensure that there will still be a stable supply of grain from the United States. One measure of how consistent irrigated maize yields have been in Nebraska is with a sensitivity analysis, which in this case is defined as the slope of the maize yield trend line from 1950-2009 divided by the root mean square error over the same period. Figure 1 shows that irrigated yields in Nebraska have a higher sensitivity (i.e., more consistent) than rainfed yields in states to the east (Iowa, Illinois, and Indiana), particularly in central and western Nebraska where almost all of the maize was irrigated according to a 2005 Land Use map produced by the Center for Advanced Land Management Information Technologies (CALMIT; Fig. 2) .

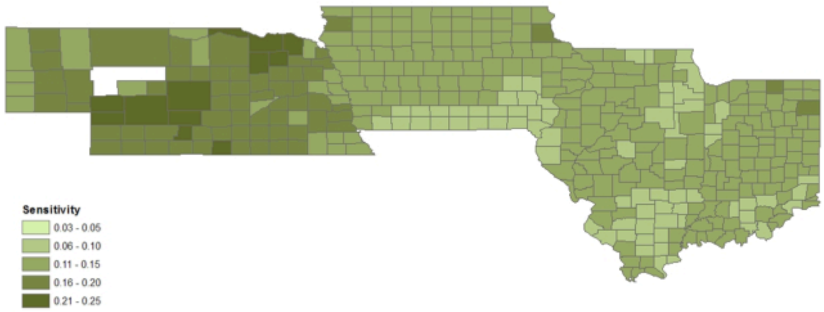

Figure 1. Comparison of irrigated maize yield sensitivity in Nebraska to rainfed maize yield sensitivity to other large maize producing states at a comparable latitude.

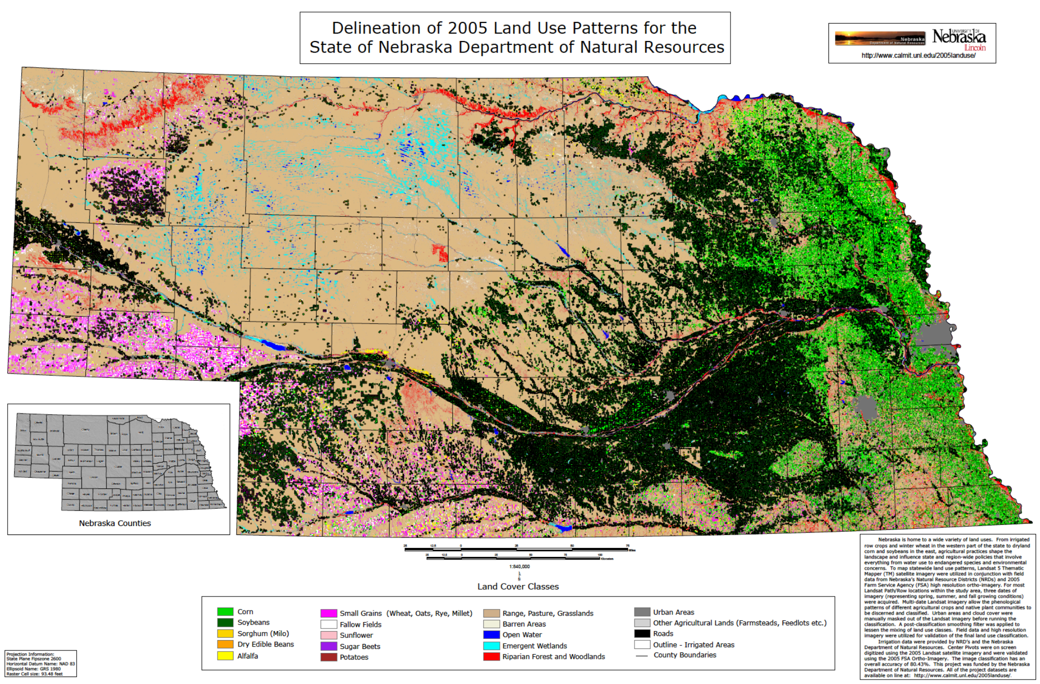

Figure 2. Land use map of Nebraska produced in 2005 by the Center for Advanced Land Management Information Technologies (CALMIT). Center pivots were overlain on the land use map and appear as the dark green that is prevalent throughout central Nebraska.

The economic benefits of this irrigation are also significant, not just because it results in more potential profit for producers, but also because these profits are often invested in new-equipment and better technology that allow producers to be more efficient. Local governments and schools also benefit from irrigation as the higher value of land generates more revenues. Thus, irrigation is the "life blood" of many areas of rural Nebraska, particularly west of Seward.

However, these tremendous benefits are not without costs or concerns. In many areas of Nebraska, groundwater depletion has been significant over the past several decades (Fig. 3) and irrigation restrictions were enforced in some areas of the state after the last major drought in 2012. Judicious use of groundwater (and all water) resources is therefore essential across the state (Bleed et al. 2015). Thankfully there are efforts underway to help producers effectively schedule irrigation treatments to minimize the over-depletion of groundwater

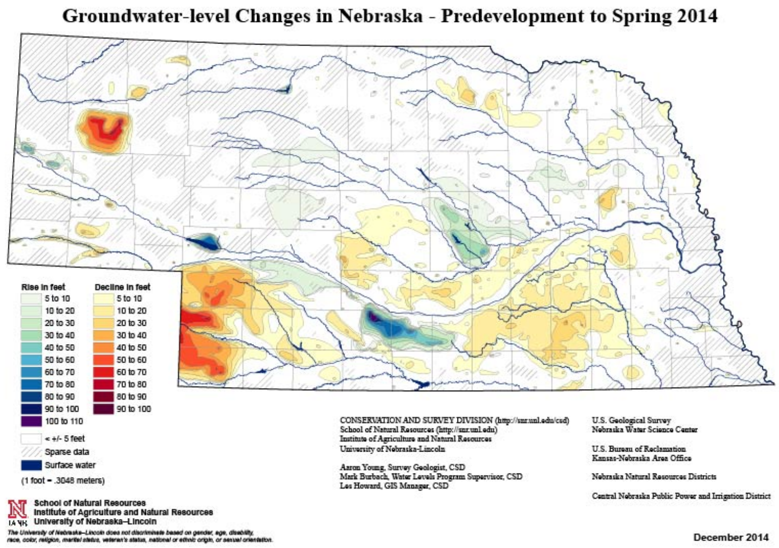

Figure 3. Groundwater changes across Nebraska since the development of irrigation wells across the state in the middle 20th century. Map courtesy of the UNL Conservation and Survey Division (CSD).

The Nebraska Agricultural Water Management Demonstration Network (Irmak et al. 2010) was developed in 2005 as a partnership between the University of Nebraska-Lincoln (UNL) Extension and the Upper Big Blue Natural Resources District (NRD) with a goal of helping producers make more informed decisions about irrigation through the installation of soil moisture sensors and evapotranspiration (ET) gages. The network (since renamed the Nebraska Agricultural Water Management Network) now has over 500 participants and some producers have reported savings of 3 inches (75 mm) of water via irrigation thanks to the data from the soil moisture sensors and ET gages.

The previous paragraph demonstrates how essential knowledge of soil moisture and biophysical variables, such as ET, can be in helping inform producers about irrigation decisions. Long-term field-scale averages of soil moisture and biophysical data have been somewhat rare to date but a significant void in this area was filled with the establishment of the ongoing UNL Carbon Sequestration Project (CSP) in 2001 at the University of Nebraska-Lincoln Mead Agricultural Research and Development Center (ARDC) near the towns of Ithaca and Mead, NE.

The ARDC is located in east-central Nebraska and is situated about 35 kilometers to the north-northeast of Lincoln and about 25 kilometers to the west-southwest of Omaha, the state's largest city. Its location in east-central Nebraska puts it at the western edge of what is commonly referred to as the U.S. (dryland) Corn Belt and just to the east of one of the most heavily irrigated places in the U.S. (Johnson et al. 2011). It is at this site where my dissertation research has been focused.

As mentioned earlier, the CSP is still ongoing today but the study period for this research was an eight-year period from 2002 to 2009. This period was chosen because it represented a period of consistent maize-soybean rotations and management practices at the two fields used in analysis and because of the diversity of the agro-climatological conditions experienced during that time. The two fields used for analysis in the dissertation, consisted of a field with an irrigated, maize-soybean rotation (IMS) and a field with a rainfed, maize-soybean rotation (RMS). These two field sites were chosen because of the same crop was grown in both field during each of the study period (i.e., the crop rotation was identical) and because management practices were consistent during that time. The study period chosen had conditions that ranged from unusually moist to average to excessively dry when compared to the 30-year period of record at Mead. Temperatures were slightly above the 1 May-30 September average of 20.6°C in four of the seven seasons, though only 2002 was more than 1.0°C above that average, and slightly below that average in two others. Only 2009 was more than 1.0°C below the 30-year average. Additional information on the sites is contained in section 1.5 of this chapter.

2.0 Problem Statement

Soil moisture is an integral part of the hydrologic cycle and an essential component in our understanding of land-atmosphere interactions. Agriculture production, particularly of maize and soybeans, are a major component of Nebraska's economy and identity. Even with increased use efficient center-pivot irrigation technology and improved genetics for drought tolerance, producers are still vulnerable to major droughts and are often under legal obligations to only use a certain amount of water per season for irrigating crops. It therefore is as important as ever to understand the link between precipitation, soil moisture, and crop stress for decisions about when and how much to irrigate. The goal of the dissertation is to demonstrate the link between soil moisture and other biophysical variables, such as ET and GPP, over an eight-year period that included abnormally wet and dry conditions from a study site that is uniquely situated in a transition zone from the semi-arid High Plains to the west and the sub-humid Corn Belt to the east.

3.0 Research Questions

1) How does soil water in a rainfed field located in an agro-climatological transition zone vary within and between growing seasons and how does it compare to a nearby irrigated field during anomalously wet and dry periods?
2) How does soil water relate to biophysical variables, such as evapotranspiration and gross primary productivity, and the surface energy budget at both a rainfed and irrigated maize field in wet and dry seasons?
3) How did soil water and biophysical variables compare to short-term and long-term drought indices during a flash drought in the 2003 growing season?

4.0 Background and Literature Review

4.1 Drought Monitoring

During parts of the study period, drought conditions were prevalent at Mead and throughout the state and surrounding region. Drought is a natural, recurring phenomena that occurs everywhere at various points in time and is occurring somewhere on Earth at any given point of time. Drought is a complex topic with ecosystem impacts that vary with its intensity and duration and socio-economic impacts that often magnify problems for agricultural producers and the most vulnerable members of society. Perhaps the most telling factor for the true complexity of drought is the lack of a true universal definition and is often considered in four broad categories defined by Wilhite and Glantz (1985): meteorological, agricultural, hydrological, and socioeconomic.

Meteorological drought is typically referred to as some deficit of precipitation from normal over a period of time. Agricultural drought refers to loss or decline of soil moisture, groundwater, and irrigation sources, such as streamflows, that lead to reductions in crop yield, forage quality, and water for livestock. Hydrological drought refers to declines in streamflows, lake levels, and reservoir levels from a prolonged period of precipitation deficits. An increased frequency of irrigation treatments can help offset agricultural impacts during drought but it can exacerbate hydrological impacts as a consequence. Socio-economic drought broadly refers to inter-linked societal and economic impacts that result from the three aforementioned drought categories. Socio-economic impacts can be the most severe and longest lasting in duration but are often difficult to quantify and/or separate from other factors.

Even though drought is often viewed within the four categories, there is often significant overlap and linkages amongst them. Meteorological drought, or a deficit of precipitation, can be viewed as the foundation for the other three categories of drought. In other words, meteorological drought *can* be mutually exclusive and independent of the other categories but agricultural, hydrological, and socioeconomic droughts are dependent on a deficit of precipitation. While all aspects of drought are important, the primary drought focus in this dissertation will be on agricultural drought.

Drought has often been quantified with climate-based drought indices. One of the first was the Palmer Drought Severity Index (PDSI), which was developed by Palmer (1965) to achieve an objective of "developing a general methodology for evaluating drought in terms of an index that permits time and space comparisons of drought severity." The PDSI is calculated from a simple water balance model that uses five factors: precipitation, potential evapotranspiration (Thornthwaite 1948), recharge, runoff, and soil moisture loss to determine whether recent precipitation was sufficient to maintain a normal water balance.

The PDSI is divided into 11 categories ranging from extreme drought to extreme wet spell (Heim 2002). Empirical constants for climate characteristic and duration factors used in the calculation were derived from data across nine locations in seven U.S. states. This has been a source of criticism for the PDSI as its performance has often failed to reflect differences in climate regimes, particularly in the western U.S. (Alley 1984; Guttman et al. 1992; Guttman 1997; Heim 2002; Wells et al. 2004). Some of the issues with the PDSI were resolved with the development of the Self-Calibrating Palmer Drought Severity Index (SC-PDSI). Wells et al. (2004) replaced the empirical constants of the PDSI with dynamic and location specific values and the SC-PDSI showed lower frequencies of extreme wet and drought conditions than the PDSI when tested at several locations in the U.S. Great Plains. Thus, the SC-PDSI represents more realistic variability and frequency of extreme events than the PDSI.

Mavromatis (2007) found that the SC-PDSI explained 92 percent of wheat variability in southern Greece. Dubrovsky et al. (2009) further found that the SC-PDSI exhibited a wider spectrum of drought conditions across the Czech Republic than the SPI due to its inclusion of temperature. However, like the PDSI, the SC-PDSI still has a fixed temporal scale and an autoregressive characteristic that allows for the index to be affected by conditions up to four years prior (Guttman 1998). These and other issues with the PDSI led to the development of normalized drought indices over the past twenty years.

McKee et al. (1993) developed the Standardized Precipitation Index (SPI) in response to demand from Colorado decision makers for an index that expressed current conditions in terms of water supply, deficit, and probability. Since precipitation is generally not normally distributed, a transformation was applied to the probability of observed precipitation for a set time period. A 3-parameter Pearson-Type III distribution was found to be the best universal model for calculation of the SPI (Guttman 1999). A thorough description of the SPI calculation is contained in Lloyd-Hughes and Saunders (2002). The SPI has the advantage of being spatially invariant and an indicator of drought on multiple time scales (Guttman 1999), though caution has been advised when comparing the SPI between sites with very different periods of record and at short time scales during distinct dry seasons (Wu et al. 2005).

The SPI has been widely used for operational and research purposes. Hayes et al. (1999) showed that the SPI detected drought conditions a full month ahead of the PDSI during the U.S. southern plains drought of 1996. Livida and

Assimakopoulos (2004) used the SPI to show that mild and moderate drought were more common on the three- and six- month time scale across northern Greece while severe drought was more frequent across southern Greece. Brown et al. (2008) integrated the SPI with satellite derived vegetation metrics and biophysical data to produce 1-km maps of the Vegetation Drought Response Index (VegDRI). McRoberts and Nielsen-Gammon (2012) used daily precipitation from the Advanced Hydrologic Prediction Service multisensor precipitation estimates (MPE) and Cooperative Observer Program (COOP) station data to obtain a high resolution SPI to be used for guidance for the U.S. Drought Monitor (Svoboda et al. 2002).

One criticism of a precipitation-only index like the SPI is that it does not account for temperature effects on drought. For example, Hu and Wilson (2000) showed that the PDSI was equally affected by large anomalies of temperature and precipitation in the central United States. Vicente-Serrano et al. (2010) addressed this issue with the development of the Standardized Precipitation Evaporation Index (SPEI). The SPEI is calculated with the same procedure as the SPI as it based on the monthly (or weekly) difference between precipitation and potential evapotranspiration (ET_p), using the ET_p method from Thornthwaite (1948). The Thornthwaite method of ET_p was chosen over more robust methods, such as Penman-Monteith (Monteith 1964), due to the simplicity of its calculation and its reasonable performance when calculating a drought index, such as the PDSI (Mavromatis 2007).

The incorporation of temperature into the SPEI also makes it more sensitive to increased frequency and severity of droughts. For example, McEvoy et al. (2011) found that the SPEI was an improvement over the SPI at identifying longer durations of severe drought in Nevada and eastern California. Potop and Mozny (2011) found that the SPEI depicted increasing drought severity in the Czech Republic over the past few decades with warming temperatures. Thus, the SPEI is an adequate index at assessing the impact of climate change (Begueria-Portugues et al. 2010).

The development of drought indices allows for useful comparison of conditions between locations and over long periods of time. However, caution should still be applied when applying an index to long time-series of climate data. Inhomogeneities in data from station relocations, instrumentation changes, and growth of vegetation and urban boundaries do exist and analyses can be erroneous if these items are not accounted for (Peterson et al. 1998). Nevertheless, climate-based drought indices are useful at identifying the severity and duration of drought.

When considering agricultural drought, the emphasis is often on impacts that occur over a shorter period of time (e.g., over part of a growing season). Short-term droughts, commonly referred to as “flash” droughts, can occur within a longer period of normal or above normal precipitation and bring devastating agricultural impacts. For example, although precipitation was above normal in most of Oklahoma during 1998, an intense, flash drought during the summer decimated the state’s cotton and peanut crop (Basara et al 1998; Arndt and Johnson 2002). In recent years, flash drought has increasingly been quantified by specialized metrics and indices developed from climate and remotely sensed data.

For example, Otkin et al. (2014) developed a Rapid Change Index (RCI) that identifies areas undergoing rapid moisture stress depicted by the Evaporative Stress Index (ESI; Anderson et al. 2013) generated by the Atmosphere-Land Exchange Inverse (ALEXI) surface energy balance model (Anderson et al. 1997, Anderson et al. 2007b). Otkin et al. (2015) then applied a simple statistical method to the RCI to determine if further intensification of flash drought was likely. While these aforementioned studies were focused more on determining water stress from flash drought from thermal band imagery, soil moisture was considered a very important factor in all of them.

4.2 Soil Moisture Monitoring

Soil moisture may be one of the best indicators of flash drought if there are previous years of data to compare against, as shown with a soil moisture index (SMI) developed by Hunt et al. (2009). However, longer-term in-situ soil moisture data from under crop cover that could further validate metrics like the RCI or help to improve our understanding of the soil-plant-atmosphere relationship in times of drought stress have been somewhat rare to this point. Thus, one of the primary goals of this dissertation is to increase our understanding of the relationship between soil moisture and biophysical indicators of crop moisture stress (e.g., reduced ET) on a true field scale during shorter dry spells and during a true flash drought.

Soil moisture is an integral part of the Earth's hydrologic cycle. The standard soil water balance equation is given as follows by Hillel (2004) in Equation 1.1:

$$dS/dt = P - ET - R - Dr \tag{1.1}$$

where δS/δt, P, ET, R, Dr are the change in soil water, precipitation, evapotranspiration, runoff, and drainage over a time period t. Soil water movement into soils is based on the conservation mass. Thus, the rate of infiltration into a soil must be equaled by a change in water content (Eq. 1.2):

$$\partial\theta/\partial t = -\partial q/\partial z \tag{1.2}$$

Soil moisture flow in unsaturated soils is based on Darcy's Law (Eq. 1.3), which essentially states that the flow into a soil is proportional to the hydraulic gradient:

$$q = -K\,\partial H/\partial z \tag{1.3}$$

where q is the flux of water, K is the hydraulic conductivity (mm s^{-1}), and $\frac{\partial H}{\partial z}$ is the hydraulic gradient (mm). However, during periods of successive wetting and drying phases, soils often have high levels of hysteresis. This issue is solved using by combining the principles of the conservation of mass from Eq. 1 and Darcy's Law in Eq. 2 to obtain the Richards equation (Eq. 2.4).

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial(z+\psi)}{\partial z}\right) \tag{1.4}$$

Since the flow is driven by the pressure of overlying water (z) and the suction of capillary action drawing water down (ψ), we write the hydraulic gradient in the Richards equation as H = z + ψ. Assuming that $\frac{\partial z}{\partial z}$=1, $\frac{\partial \psi}{\partial z} = \frac{\partial \psi}{\partial \theta} \cdot \frac{\partial \theta}{\partial z}$, and $K \cdot \frac{\partial \psi}{\partial \theta}$ is the soil water diffusivity (i.e., the combination of conductivity and capillary pressure), we obtain a modified form of Richards equation (Eq. 1.5):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K + D\frac{\partial \theta}{\partial z}\right) \tag{1.5}$$

The Richards equation is often simplified into the Green and Ampt infiltration equation, which assumes a solid wetting front that proceeds downward at a constant rate with constant matric (ψ) suction. Thus, the wetting front is considered to be a plane that separates a uniformly infiltrated zone with a zone with no infiltration. Infiltration (Eq.1.6) is then considered to be the product of the depth of the wetting front (L_f) and θ.

$$I = Lf \cdot \Delta\theta \tag{1.6}$$

The rate of advance of the wetting front is inversely proportional to the cumulative infiltration and assuming that the rate of infiltration is equal to the product of hydraulic conductivity and the change in pressure head over the wetting front, we obtain Eq. 1.7

$$\Delta\theta\frac{dLf}{dt} = K\frac{\Delta H_p}{Lf} \tag{1.7}$$

After further manipulation (see Hillel 2004 for further details) and assuming time is large, the Green and Ampt approach simplifies to a delta function approximation (Eq. 1.8) such that δ can assumed to be a constant.

$$I \sim Kt + \delta \tag{1.8}$$

Thus, over a period of time after precipitation, the amount of infiltration can be approximated to be the product hydraulic conductivity and time plus a constant. Even though soil water infiltration is not discussed in great technical detail in this dissertation, it was important to show (via the past several equations) that hydraulic conductivity is a critical parameter in soil water infiltration. Exact measures of hydraulic conductivity cannot be inferred in the CSP fields; however, other laboratory measurements allowed for calculation of saturated hydraulic conductivity via pedotransfer functions in Saxton and Rawls (2006). Thus the ability of soils to infiltrate precipitation can be inferred at different areas within the CSP fields. This is discussed further in section 1.5.

4.3 Biogeochemical Fluxes of Crops

Since its inception in 2001, the CSP has collected a wealth of flux (carbon and energy) observations. These data are renowned enough to be used for validation in irrigation modeling simulations at NASA Goddard Space Flight Center (Lawston et al. in press) and for test cases in the Joint UK Land Environment Simulator (JULES) model (Best et al. 2011). There is currently a goal of making the Mead ARDC a testbed site for instrument calibration and validation of land surface model output (UNL Newsroom 2014). Thus, the data used in the dissertation are likely to be more in demand in the future due to increased exposure.

Several works have been published, particularly in the realm of energy and carbon balance. In Suyker et al. (2004), the authors presented results of net ecosystem CO_2 exhange (NEE) and gross primary productivity (GPP) during the first year (2001) of the CSP. A dry and hot spell in the middle of that growing season reduced leaf area index (LAI) and NEE at the rainfed maize soybean rotation (RMS) compared to the irrigated maize soybean rotation (IMS).

Verma et al. (2005) wrote a detailed report on carbon exchange at all three CSP fields during the first four seasons (2001-2004) of the project. They reported that GPP was almost twice as high in a maize season as in a soybean season and that net ecosystem production (NEP) was about the same in the rainfed and irrigated field, as increased respiration in irrigated fields with higher soil moisture offset the higher GPP at the irrigated sites compared to RMS.

Suyker and Verma (2009) presented detailed results from six years (2001-2006) of evapotranspiraton (ET) data at ICM, IMS, and RMS. Growing season ET accounted for an average of 84 and 72 percent of the annual evaporation at the irrigated sites (ICM, IMS) and RMS respectively. As expected, annual ET was higher at the irrigated sites than at RMS, particularly during the flash drought that occurred during the 2003-2004 season, and was higher in maize years than in soybean years at both IMS and RMS. The authors also showed that the crop coefficient (Kc), which is calculated as the ratio of ET to reference ET (ET_o), was as much as 30 percent higher at IMS than at RMS during the middle of the 2003 flash drought.

A similar study with GPP over the 2001-2006 growing seasons sites showed that the seasonal distributions of GPP were consistent in maize and soybeans throughout the six seasons and that GPP was consistently higher in the irrigated fields than at RMS (Suyker and Verma, 2010). This was especially true in the 2003 growing season when cumulative GPP was reduced by 24 percent at RMS compared to IMS. The authors also showed that there was no statistical difference in the ET/ET_o-LAI relationship compared to that of GPP-LAI.

In Suyker and Verma (2012), the authors showed that green leaf LAI was a dominant factor in explaining interannual variability of GPP in maize, whereas both LAI and photosynthetically active radiation (PAR) were dominat factors for soybeans. As also shown in earlier results, mean annual GPP of soybeans was significantly less than that of maize. However, in this paper the authors presented results of how much of the GPP was eventually lost to respiration. In a maize year, nearly 70 percent of accumulated GPP in maize was lost to respiration. This seems like a lot until one considers that almost all of the accumulated GPP in the soybean years was lost to respiration. Thus, both RMS and IMS were approximately carbon neutral over several seasons, with IMS being a slight carbon source in the early years due to enhanced respiration rates compared to the drier RMS.

5.0 Study Site Description

The CSP is located at the University of Nebraska-Lincoln (UNL) Agricultural Research and Development Center in east-central Nebraska near the towns of Ithaca and Mead, NE. The CSP is located in the north central United States (Fig. 4a) and is roughly 45 km to the northeast of downtown of Lincoln, Nebraska and 43 km to the west-southwest of downtown Omaha, Nebraska. The CSP consists of three sites. The first agroecosystem is an irrigated, continuous maize (ICM) site centered at 41˚09'54.2" N, 96˚ 28'35.9" W with an irrigated area of 48.7 ha. The second agroecosystem is an irrigated, rotated maize-soybean (IMS) site centered at 41˚09'53.5" N, 96˚ 28'12.3" W with an irrigated area of 52.4 ha. Both ICM and IMS were irrigated rotations of maize and soybeans under no-till in the ten years prior to the initialization of the CSP. The third agroecosystem is a rainfed, rotated maize-soybean (RMS) site centered at 41˚10'46.8" N, 96˚ 26'22.7" W with an area of 65.4 ha. Prior to the CSP, RMS had 2-4 ha plots of maize, soybeans, wheat, and oats with tillage (Verma et al. 2005).

The Mead Automated Weather Data Network (AWDN) station, roughly 5 km from RMS, was set up for research purposes in the spring of 1981 and has since become an operational weather station managed by the High Plains Regional Climate Center. It is not part of the CSP, but its data is used in Chapter 2 for a precipitation climatology. Figure 4b shows a close-up Google Earth image of the three CSP sites and the Mead AWDN site. Figure 4c (4d) shows a close-up Google Earth image of the ICM and IMS (RMS) fields.

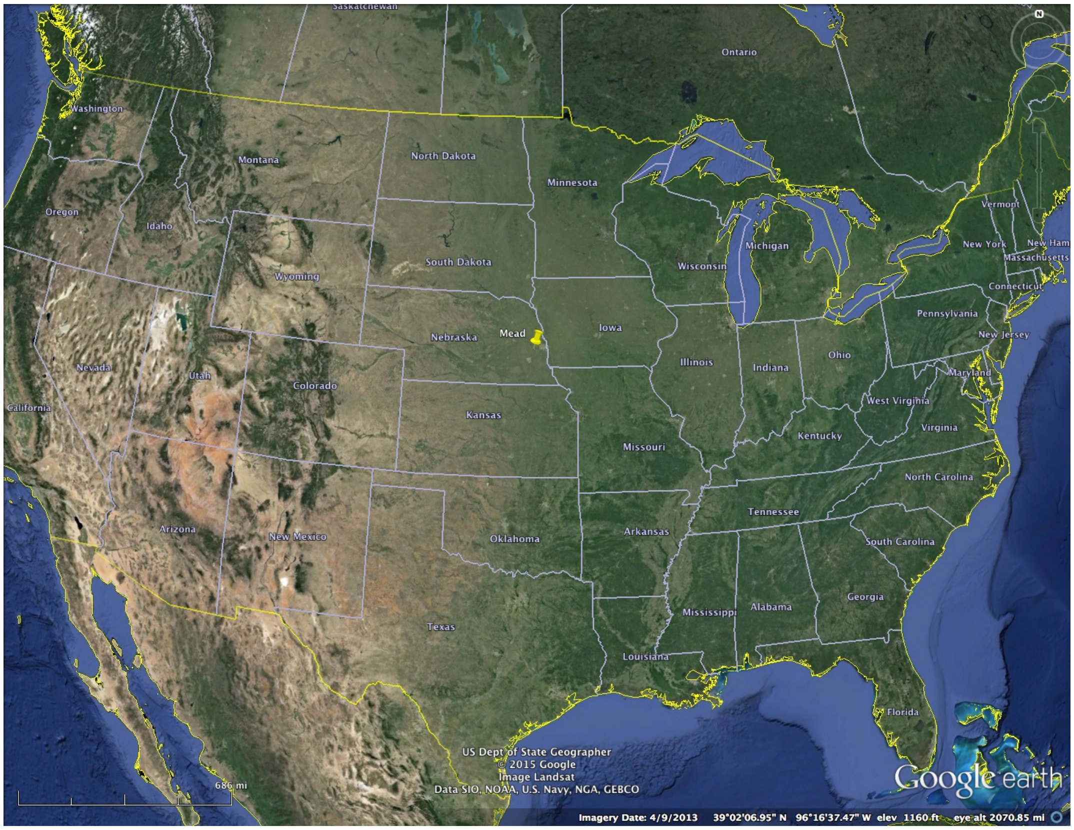

Figure 4a. The location of the CSP sites and the Mead AWDN site in relation to the rest of the continental United States.

Figure 4b. Aerial view of the UNL Mead ARDC. Pins denote the middle of the irrigated continuous maize (ICM) irrigated rotated maize-soybean (IMS) and rainfed rotated maize-soybean (RMS) fields of the Carbon Sequestration Project and the Mead AWDN site that has been operating since 1981.

Figure 4c. Zoomed image of ICM and IMS fields in the CSP.

Figure 4d. Zoomed image of the RMS field in the CSP.

5.1 Intensive Management Zones

Each CSP site consists of six, 20 m x 20 m intensive management zones, hereafter referred to as IMZ's, where detailed process-level studies of soil water, soil carbon dynamics, canopy and soil gas exchange, crop growth and biomass partitioning are established. Prior to the onset of the CSP in 2001, all three sites were uniformly tilled by disking the top 10 cm to incorporate Phosphorous (P) and Potassium (K) fertilizers and to homogenize the soil layer (Suyker and Verma, 2009). Nitrogen (N) fertilizer applications were applied to IMS and RMS prior to planting in 2003; subsequent N applications were applied in June at IMS through the center-pivot system in a process known as fertigation.

The IMZ locations were selected using k-means clustering applied to six layers of environmental site information for 4 m x 4 m cells based broadly on soil type, topography, and crop production potential across each site. Fine-scale spatial information used for each site included a digital soil map, a digital elevation model, a Veris map of soil electrical conductivity (0-30 cm), near infrared reflectance of bare soil from the IKONOS satellite (4 km resolution), and a map of soil organic matter (0-20 cm). Interpolation onto a 4 x 4 m grid was done by kriging. The footprints of the IMZ's are not equal in area and thus field-averaged calculations of soil water are weighted using Equation 1.9 below, where w_i is the weight (i.e., fraction of the field represented by the fuzzy classes associated with the i'th IMZ), x is the measured soil water in the i'th IMZ and i increases from 1 to n (the total number of IMZs per field):

$$x_{avg} = \Sigma(w_i x_i) \quad (1.9)$$

Weights were assigned to each IMZ based on the proportional area of the soil fuzzy class represented.

Prior to this study, soil samples were collected from IMZ's of the three sites and then analyzed in the laboratory for water retention curves and soil parameters, such as bulk density. Saturation (θ_s) was calculated (Eq.1.4) from bulk density values obtained from the laboratory. In equation 10, ρ_B is the bulk density (Mg/m^3) and ρ_p is the particle density, (assumed to be approximately 2.65 Mg/m^3 for this study):

$$\theta_s = 1 - \rho_B/\rho_p \quad (1.10)$$

Field capacity (θ_{FC}) and wilting point (θ_{WP}) values were determined from moisture release curves obtained from laboratory work. Saturated hydraulic conductivity (K_s) was calculated from aforementioned values of θ_{FC}, θ_{WP}, and θ_s using algorithms in Saxton and Rawls (2006).

5.2 Soil Characteristics

The following sub-sections give a description of the soil characteristics at ICM, IMS, and RMS.

5.2.1 ICM

Soil textures at ICM are predominantly a Yutan silt clay loam with moderate to high amounts of organic matter. Bulk densities at ICM average 1.26 Mg/m^3, 1.34 Mg/m^3, 1.42 Mg/m^3, and 1.42 Mg/m^3 at 10 cm, 25 cm, 50 cm, and 100 cm respectively (Table 1).

Location	Depth	Texture	θ_{FC}	θ_{WP}	ρ_B
ICM 4	10	sicl	0.370	0.197	1.25
ICM 4	25	sicl	0.431	0.143	1.31
ICM 4	50	sil	0.405	0.091	1.41
ICM 4	100	sic	0.440	0.299	1.42
ICM 5	10	sicl	0.343	0.174	1.21
ICM 5	25	sicl	0.401	0.252	1.32
ICM 5	50	sic	0.418	0.271	1.38
ICM 5	100	sic	0.420	0.252	1.44
ICM 6	10	sicl	0.391	0.197	1.32
ICM 6	25	sicl	0.419	0.253	1.39
ICM 6	50	sicl	0.416	0.270	1.47
ICM 6	100	sicl	0.422	0.240	1.41

Table 1. Soil parameters at ICM determined directly from laboratory work. Locations are given by the IMZ number at ICM. Depths of soil moisture sensors are listed in centimeters (cm). The texture legend is as follows: sicl (silt clay loam), sil (silt loam), and sic (silt clay).

Soil water at ICM was affected by changes in management practices. From 2001-2005, ICM was managed as a no-till, continuous maize field. However, the amount of litter and residue from five seasons of this practice had several detrimental effects. Suyker and Verma (2009) reported non-uniformity in plant populations from impedance in the sowing operation, a reduction in nitrogen use efficiency (NUE), and an increase in disease and insect damage. The latter impact is due to the survival rate of pathogens in crop residue from the previous years (Bockus and Shroyer, 1998). The combination of these effects led to declining yields and a conservation plow was utilized after harvest in the fall of 2005 and every successive harvest thereafter. The conservation plow was chosen over other standard tillage equipment because it minimizes soil disturbance and vertically distributes around 2/3 of the residue within the top 25 cm of the soil, leaving the remaining 1/3 on the soil surface.

Even though care was taken to avoid significant soil disturbances, the conservation plow was used while the field was still a bit wet, which led to compaction and an increase in bulk density at ICM. The effect of tillage at ICM was not consistent across IMZ's and was most significant in 2006. The effect of conservation tillage was less pronounced in years after 2006 and the average water content (θ) at ICM 4 and ICM 5 was back around 2002-2005 levels by the 2007-2009 seasons. However, given the field management differences at ICM within the study period, and the field management and cropping differences between ICM and the two rotated sites, IMS and RMS, it was decided to exclude ICM from analysis throughout the remainder of the dissertation. That is not to imply that valuable data don't exist from ICM; many papers have been published with the data from ICM. Rather the focus and scope of the dissertation is more strongly tied to direct comparisons of soil water and biophysical measurements between a common crop at a rainfed and irrigated site (i.e., between RMS and IMS).

5.2.2 IMS

Soils at IMS are a mix of the Yutan, Tomek, and Filbert series with silt clay loam as the dominant soil texture. Bulk densities at IMS average 1.48 Mg/m^3, 1.48 Mg/m^3, 1.40 Mg/m^3, and 1.38 Mg/m^3 at 10 cm, 25 cm, 50 cm, and 100 cm respectively (Table 2). Organic matter was high at all three IMZ's with soil water measurements and IMS was consistently the highest yielding field in the CSP. With a consistent maize-soybean rotation, IMS did not have the accumulation of residue that occurred at ICM, and therefore did not undergo conservation tillage at the end of any season during the eight years of the study.

Location	Depth	Texture	θ_{FC}	θ_{WP}	ρ_B
IMS 2	10	sicl	0.377	0.236	1.49
IMS 2	25	sicl	0.413	0.275	1.49
IMS 2	50	sicl	0.431	0.273	1.47
IMS 2	100	sicl	0.423	0.241	1.35
IMS 5	10	sicl	0.436	0.288	1.46
IMS 5	25	sicl	0.433	0.244	1.49
IMS 5	50	sicl	0.448	0.263	1.39
IMS 5	100	sicl	0.445	0.255	1.36
IMS 6	10	sicl	0.396	0.221	1.48
IMS 6	25	sicl	0.423	0.219	1.46
IMS 6	50	sicl	0.413	0.243	1.35
IMS 6	100	sicl	0.446	0.287	1.43

Table 2. Soil parameters at IMS determined directly from laboratory work. Locations are given by the IMZ number at IMS. Depths of soil moisture sensors are listed in centimeters (cm). The texture legend is as follows: sicl (silt clay loam).

5.2.3 RMS

Soils at RMS are a mix of the Fillmore, Tomek, Yutan, and Filbert series and are mostly silt clay loam in texture. Soils at RMS are deep and high in organic matter. Bulk densities at RMS average 1.35 Mg/m^3, 1.31 Mg/m^3, 1.35 Mg/m^3, and 1.30 Mg/m^3 at 10 cm, 25 cm, 50 cm, and 100 cm respectively (Table 3). Prior to the beginning of CSP in

2001, RMS had a diverse cropping history that consisted of wheat, barley, oats, soybeans, and maize

Location	Depth	Texture	FC	WP	ρ_B
RMS 1	10	sicl	0.381	0.171	1.33
RMS 1	25	sicl	0.397	0.184	1.30
RMS 1	50	sicl	0.361	0.194	1.36
RMS 1	100	sicl	0.328	0.176	1.31
RMS 2	10	sic	0.377	0.231	1.23
RMS 2	25	sic	0.426	0.261	1.29
RMS 2	50	sicl	0.409	0.259	1.40
RMS 2	100	sil	0.382	0.199	1.24
RMS 3	10	sic	0.452	0.275	1.47
RMS 3	25	sicl	0.442	0.243	1.34
RMS 3	50	sicl	0.430	0.246	1.37
RMS 3	100	sicl	0.410	0.201	1.26
RMS 5	10	sicl	0.429	0.195	1.37
RMS 5	25	sicl	0.408	0.233	1.31
RMS 5	50	sicl	0.402	0.256	1.27
RMS 5	100	sicl	0.434	0.262	1.39

Table 3. Soil parameters at RMS determined directly from laboratory work. Locations are given by the IMZ number at RMS. Depths of soil moisture sensors are listed in centimeters (cm). The texture legend is as follows: sicl (silt clay loam), sil (silt loam), and sic (silt clay).

5.3 Soil Parameter Variability

Two soil hydraulic parameters that are vital for soil water flow are discussed in this section: porosity (or saturation; θ_s) and saturated hydraulic conductivity (K_s).

The former was obtained from field samples and the latter was calculated via pedotransfer functions (PTF's) given in Saxton and Rawls (2006). Soil hydraulic parameters can also be estimated via remotely sensed soil moisture (Santanello et al. 2007; Harrison et al. 2012) and are critical for determining soil moisture in land surface models such as the Noah land surface model (Ek et al. 2003).

As reported in previous studies, results from the CSP show that θ_s was normally distributed and K_s had a lognormal distribution. Comparisons of mean and standard deviation of θ_s and $\log_{10} K_s$ are given by soil texture (Table 4a), location and depth (Table 4b), and by IMZ (Table 4c). Three soil textures (or soil classes; silt clay loam, silt loam, silty clay) are found throughout the CSP, but only silt clay loam had a large enough sample size to be statistically significant (α =0.05 level). Nevertheless, the silt clay loam means of θ_s and $\log_{10} K_s$, which are 0.482 m^3/m^3 and -0.63 mm/hr respectively, compare favorably to the means of 0.464 m^3/m^3 and -0.54 mm/hr for θ_s and $\log_{10} K_s$ reported in Cosby et al. (1984).

		θ_s		log K_s	
Texture	n	Mean	Std. Dev	Mean	Std. Dev
SICL	32	0.482	0.029	-0.63	2.25
SIC*	6	0.491	0.030	-0.74	1.96
SIL*	2	0.499	0.046	1.26	1.33
ALL	40	0.484	0.029	-0.55	2.18

Table 4a. Mean and standard deviation of two soil parameters (porosity and the log of saturated hydraulic conductivity) obtained from lab measurements for different soil textures at the three field sites (ICM, IMS, RMS). The asterisk (*) indicates the sample size was not large enough sample to be considered statistically significant.

		θ_s		log (K_s)	
Location and Depth	n Textures	Mean	Std. Dev.	Mean	Std. Dev.
ICM 10 cm	1	0.525	0.021	2.25	0.83
ICM 25 cm	1	0.494	0.016	0.20	0.84
ICM 50 cm	3	0.463	0.017	-1.60	2.64
ICM 100 cm	2	0.463	0.006	-2.11	1.03
IMS 10 cm	1	0.444	0.007	-2.06	2.23
IMS 25 cm	1	0.485	0.029	-0.55	2.18
IMS 50 cm	1	0.471	0.024	-2.13	2.21
IMS 100 cm	1	0.479	0.017	-2.08	2.33
RMS 10 cm	2	0.503	0.023	0.43	1.85
RMS 25 cm	2	0.506	0.008	0.51	1.04
RMS 50 cm	1	0.491	0.021	0.43	1.32
RMS 100 cm	2	0.510	0.025	1.19	1.93

Table 4b. Mean and standard deviation of two soil parameters (porosity and the log of saturated hydraulic conductivity) obtained from lab measurements for 12 location and depth combinations at ICM, IMS, and RMS respectively.

		θ_s		log (K_s)	
IMZ	n(Textures)	Mean	Std. Dev.	Mean	Std. Dev.
ICM 4	3	0.491	0.031	-0.06	2.31
ICM 5	2	0.495	0.037	0.40	2.11
ICM 6	1	0.473	0.023	-1.29	2.48
IMS 2	1	0.453	0.025	-1.80	1.86
IMS 5	1	0.464	0.023	-3.41	1.45
IMS 6	1	0.461	0.022	-1.94	2.10
RMS 1	1	0.500	0.009	1.87	0.53
RMS 2	3	0.513	0.030	1.16	1.31
RMS 3	2	0.499	0.018	-0.53	1.38
RMS 5	1	0.496	0.025	0.05	1.38

Table 4c. Mean and standard deviation of two soil parameters (porosity and the log of saturated hydraulic conductivity) over all depths for IMZ's with soil water at ICM, IMS, and RMS. The number of soil textures in a soil profile at a given location is given in the second column from the left.

Previous studies (Gutmann and Small, 2005; Cosby et al. 1984) reported large variation in hydraulic parameters existed in other soil databases; thus it was not unexpected that variation (i.e., the standard deviation) in K_s at Mead was sometimes greater within a field or within an IMZ than across the entire study area. For example, the variation in K_s across the 50 cm depth of IMZ's at ICM and across all depths of IMZ's at IMS was larger than the variation across the entire study area (Table 3b). Two individual IMZ's (ICM 4, ICM 6) also had more variation in K_s within the soil profile than across the whole field (Table 3c). Variation in θ_s was less within fields and within IMZ's than across the entire study except across the 25 cm depth of IMZ's at IMS where the variation equaled that of the entire study area. Variation was generally less at RMS for both K_s and θ_s than at the two irrigated sites. For example, the highest standard deviation in the profile at any RMS IMZ was 1.38, which is lower than the standard deviation at any IMZ at ICM and IMS (Table 3c). This would imply more uniformity in the geometrical pore structure within the soil (Klute and Dirksen, 1986) at RMS but data are not available to prove that.

The amount of vertical and spatial variation in K_s differed between fields as well. Variation in K_s was significantly higher within the soil profile of an IMZ at ICM than at the same depth (i.e., 50 cm) across the field. Conversely, IMS had significantly higher spatial variation than vertical variation in K_s. Spatial variation in K_s was slightly higher than vertical variation in K_s at RMS. Soil texture was generally homogeneous throughout the CSP, with six of ten IMZ's having only one soil texture class (silt clay loam) and of all 40 samples, 32 of them were a silt clay loam.

6.0 Dissertation Organization

Each of these research questions highlighted earlier will be addressed in its own research chapter. Since soil water is the overarching theme throughout the dissertation, there is some overlap in data presented in each chapter. The three research chapters (Chapters 2 through 4) presented here have been written up in the format of a publishable paper and Chapter 4 was published in Agricultural and Forest Meteorology in 2014. Thus, each chapter also has information pertaining to the study site, which means there is also overlap in a few tables presented here. However, all table and figure numbers restart with the beginning of a new chapter.

Chapter 2: A soil water climatology of a rainfed field in eastern Nebraska

The objective of this chapter is to determine the relationship between soil moisture and precipitation at a rainfed agroecosystem over a period of eight years that included historically wet, historically dry, and average conditions compared to a 30-year period of record for the location. Soil moisture data from the rainfed agroecosystem (RMS) are compared to those of the irrigated agroecosystem (IMS) to better demonstrate the loss of soil moisture during dry spells at RMS. Measurements from RMS are also compared to a30-year precipitation climatology at Mead and a precipitation climatology at two High Plains sites and three other sites in the Corn Belt.

Chapter 3: The dynamic relationship between soil moisture and biophysical measurements over a maize field

The objective of this chapter is to determine the relationship of field-scale averaged soil moisture and biophysical variables, such as evapotranspiration and gross primary productivity, and its effect on the surface energy budget at both a rainfed and irrigated maize field. This chapter also shows how the lack of soil water at RMS affected the partitioning of the energy balance compared to the well-watered IMS and how significant precipitation events during dry spells led to increases, albeit brief, in implied stomatal conductance of maize plants at RMS.

Chapter 4: Monitoring the effects of rapid onset of drought on non-irrigated maize with agronomic data and climate-based drought indices

The objective of this chapter is to present a detailed analysis of a flash drought that occurred at Mead in 2003. The flash drought began in late June and lasted through the most critical time of the growing season for maize- the late vegetative and the reproductive stage. In this chapter, two standardized drought indices, the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI) are compared to soil water and biophysical data from IMS to demonstrate their utility at depicting a rapidly developing drought. Data from RMS are also compared to neighboring IMS to demonstrate the effectiveness and usefulness of irrigation during such a period.

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CHAPTER 2: A SOIL MOISTURE CLIMATOLOGY OF A RAINFED FIELD IN EASTERN NEBRASKA

Abstract:

The objective of this chapter is to show results from eight years of soil moisture measurements under a rainfed agroecosystem in a region that is uniquely situated in a transition zone between almost exclusively rainfed agriculture to the east and almost exclusively irrigated agriculture to the west. Soil moisture sensors were installed at four depths (10 cm, 25 cm, 50 cm, and 100 cm) in Intensive Management Zones (IMZ's) for the purpose of determining crucial plant-soil moisture relationships under maize and soybeans, both irrigated and rainfed conditions,, as part of the Carbon Sequestration Project (CSP) at Mead, NE. The eight years (2002-2009) of soil moisture data utilized in this study captured a range of different growing season conditions ranging from drought and flash drought events to periods significantly above-average precipitation. Soil moisture at the rainfed site correlated well with precipitation over the entirety of the study period. However, this paper shows that timing of precipitation was often more important to differences in average seasonal soil moisture than total growing season (May-October) precipitation, as total growing season precipitation did not always reflect within-season variability of precipitation. This paper shows that shallow soil moisture was most reflective of an incipient wet or dry spell within a season and deeper soil moisture was most reflective of longer-term dryness or wetness. Data from a nearby irrigated field were also analyzed to further demonstrate the importance of variability and timing of precipitation within a season, as it was critical to scheduling irrigation treatments at the irrigated site.

1.0. Introduction

This chapter resents results obtained from the analysis of eight years of soil moisture measurements at various depths under a rainfed agroecosystem an area located in the transition zone between rainfed-dominated agriculture in the U.S. Corn Belt and more intensively irrigated agriculture in the U.S. Great Plains region. Soil moisture is an integral part of the hydrologic cycle and a critical parameter for plant growth and development. Soil moisture measurements, both in-situ and satellite-derived estimates (Nghiem et al. 2012), are utilized for drought monitoring and predictions of flash flooding at a local or regional scale and for land surface modeling on regional to global scales. With the introduction of an optimization and data assimilation framework such as the NASA Land Information System (LIS; Kumar et al. 2006; Peters-Lidard et al. 2007), in-situ soil moisture measurements can be utilized for data assimilation (Kumar et al. 2008; Kumar et al. 2012) and estimation of soil hydraulic parameters, such as porosity and saturated hydraulic conductivity (Santanello et al. 2007; Harrison et al. 2012). Thus, there is likely to be increasing demand from the land surface modeling community to utilize real-time soil moisture measurements, including those under crop cover.

Unfortunately, in-situ soil moisture measurements under crop cover have been somewhat limited compared to measures under other land cover types (e.g., grass) to date, but important insights into the soil moisture-crop response have been made. Nielsen et al. (2010) showed that rainfed maize yields in northeast Colorado were highly correlated to precipitation between 16 July and 26 August and the chances for a "break-even" yield were substantially higher if sufficient soil moisture was available at planting. Meyer et al. (1993a) reported that maize was most sensitive to water stress in the silking-blister dough stage. Calvino et al. (2003) reported a curvilinear response of maize yield to available water in the three weeks preceding and following silking. Earl and Davis (2003) reported maize yield reductions up to 85% during severe water stress that occurred after the sixth leaf stage in Georgia. Soybean (*Glycine max* L.) yields are reduced significantly when water stress occurs during flowering and pod fill stages. Doss et al. (1974) and Eck et al. (1987) reported soybean yield reductions of 50 percent when water stress occurred between the flowering and beginning seed stage. Thus, it is well established that a lack of soil moisture causes vegetation stress and yield reduction during the critical growth stage(s) of crops.

Illston et al. (2004) found four distinct soil moisture phases during the year under grass cover at Oklahoma Mesonet sites that included: 1) a moist plateau in the spring, 2) a transitional drying in early summer, 3) an enhanced drying later in the summer, and 4) a recharge phase in the autumn and winter. Similar seasonal trends were also noted at Automated Weather Data Network (AWDN) sites in Nebraska (Hubbard et al. 2009a). In that case, Hunt et al. (2009) showed there was a longitudinal gradient of decreasing east-to-west precipitation that led to corresponding decreasing east-to-west gradients in soil moisture in the summer and early autumn.

Soil moisture gradients in the Illinois Soil Moisture Network varied by latitude in the winter and spring versus longitude in the summer and autumn, and an average depletion of 72 mm in the top 2 m of soil was found at sites throughout the state between the winter and summer months (Hollinger and Isard, 1994). Vinnikov et al. (1999) add that a standard deviation of 8.5% in volumetric water content existed in the top 10 cm of soil across the Illinois Soil Moisture Network over a six-year period in the 1980’s. Scott et al. (2010) also found that volumetric water content variability increased with depth between sites in a sod experiment in east-central Illinois and noted a strong relationship between observed soil moisture in the deeper layers and surface terrain slope.

Irrigated agriculture, like rainfed agriculture, continues to serve an important role in the production of cereal crops, with increasing importance in the developing world. Many areas however, including the U.S. High Plains region, are faced with the daunting task of increasing crop production with less water, as groundwater reserves become further depleted (Sophocleous, 2012). Climate change could further exacerbate limited supplies of groundwater in these regions. Thus, monitoring soil moisture under cereal crops is critical for determining the best irrigation strategies and other farming practices, such as no-till or reduced till.

In an ideal situation, soil moisture measurements under crop cover would be common on a global scale and utilized for data assimilation. Unfortunately, long-term studies of soil moisture under crop cover on a field scale, such as the 25-year study reported by Nielsen et al. (2010), have been rare. Thus, a crucial need for long-term soil moisture measurements under irrigated and rainfed crops, such as maize, was met when soil moisture sensors were installed as part of a large carbon and energy balance project called the Carbon Sequestration Project (CSP; Suyker et al. 2004; Verma et al. 2005) at the UNL research farm near Mead, NE. The long period of time over which soil moisture data were collected in the CSP, the diversity of crops and management practices under which the data were collected, and the range in meteorological conditions between growing seasons allow this study to have applicability beyond Nebraska and the U.S. Corn Belt for the key cash crops of maize and soybeans. Therefore, the overall goal of this paper is to show the variability of soil moisture under crop cover over an eight-year period at a location in a transition zone between (almost) exclusively rainfed agriculture to the east and irrigated agriculture to the west.

The location in the transition zone allows for the possibility that soil moisture measurements under crop cover in a wet year could potentially be representative of a typical season at locations further east in the U.S. Corn Belt. Conversely, it is possible that the soil moisture measurements from Mead could be representative of a rainfed field in the High Plains in a dry season. Given the importance of irrigation for high-yielding crops in a semi-arid area like the High Plains, the comparison of soil moisture under a rainfed field to soil moisture under an irrigated field in a flash drought shows the value of having irrigation to offset the lack of natural precipitation. Likewise, soil moisture measurements under a rainfed field can be very useful in better determining the relationship between soil moisture and crop stress at the field scale during a flash drought.

2.0 Materials and methods

2.1 Carbon Sequestration Project site

The CSP is located at the University of Nebraska-Lincoln (UNL) Agricultural Research and Development Center in Saunders County, Nebraska near the town of Mead. This location is roughly 35 km northeast of Lincoln, NE and is defined in Chapman et al. (2001) as being at the western edge of the Western Corn Belt Plains ecoregion. Maize and soybeans are the main crops grown in the area and according to the National Agricultural Statistics Service (NASS), about 67 percent of crops grown in Saunders County, NE where the study area is located were rainfed in the final year of the study period (2009).

This region is a sharp transition zone between almost exclusively rainfed agriculture in far eastern Nebraska that extends into the adjacent Corn Belt region to the east and the predominatelyirrigated agriculture to the west that extends into the semi-arid Great Plains. For example, Cass County, NE (just east-southeast along the Missouri River) was 99 percent *rainfed* in the final year of the study period. Meanwhile, in the same year in Merrick County, NE, which is 100 km west of the CSP sites, 94 percent of the crops were *irrigated*. Thus, the rainfed and irrigated fields of the CSP make it representative of the aforementioned transition zone in eastern Nebraska.

The CSP was initiated in the spring of 2001 and consisted of three field sites ranging in size from 49 to 65 ha. The first site has been managed as an irrigated, continuous maize (ICM) site centered at 41˚09’54.2” N, 96˚ 28’35.9” W. The second site has supported an irrigated, maize-soybean (IMS) rotation (interannual) located at 41˚09’53.5” N, 96˚ 28’12.3” W. The third site is a rainfed, rotated maize-soybean (RMS) system located at 41˚10’46.8” N, 96˚ 26’22.7” W. Most of the data used for this study was collected at RMS as its data best reflect the variability of precipitation within the study period because it was a rainfed system. Data from IMS are used for comparisons, as the crop type was the same as RMS in every growing season during this study. Data from ICM, while unique, are excluded from analysis in this chapter half the years because odifferent crops were planted (i.e., maize and soybeans). Second, management practices varied (i.e., continuous maize and a switch from no-till to conservation tillage halfway through the study period) that could inter-field soil moisture differences not related to natural precipitation or irrigation applications, which was not the focus of this research.

Maize was planted to IMS and RMS in odd numbered years and soybeans in even numbered years. The dates of specific development stages of maize and soybeans at the three sites were determined from records collected during regular field analyses by agronomists. There was usually a slight variation in a development stage within the three fields, so the date listed for a particular development stage of maize was when the majority of the crop in the field was at that stage. Reproductive stage was considered to have begun when field samples showed greater than 50 percent of a field with a maize (soybean) crop entering silking (beginning bloom). Soybeans and maize both reached physiological maturity in September, with maize typically reaching that stage slightly earlier in the month. Harvest dates were heavily influenced by weather and ranged from early October to early November. Later harvest dates were usually a result of wet conditions in October, especially in 2009 when unusually wet and cool conditions persisted throughout the month.

Maize planting density at RMS was about 75 percent of the density at IMS, with an average of approximately 62,000 plants/ha over the four years compared to an average planting density of 81,936 plants/ha for IMS. The planting density for soybeans was 370,644 plants/ha for each year soybeans were planted at IMS and RMS. Planting density for maize at RMS was lower than at IMS to limit plant competition for soil moisture in a rainfed field during dry periods. Yields for maize averaged 13.7 and 9.8 Mg/ha at IMS and RMS, respectively. Yields for soybeans averaged 3.7 and 3.4 Mg/ha at IMS and RMS, respectively. For additional details, please refer to Verma et al. (2005) and Suyker et al. (2003).

2.2 Intensive Management Zones and soil parameters

Each CSP site contained six 20 m-by-20 m IMZ’s, where detailed process-level measurements of soil moisture, soil C dynamics, canopy and soil gas exchange, crop growth and biomass partitioning were collected. Root distribution measurements, however, were not made during the study period and thus, root densities at specific depths are unknown. The two field sites were uniformly tilled by disking the top 10 cm at the beginning of the study to incorporate Phosphorous (P) and Potassium (K) fertilizers and to homogenize the soil layer (Suyker and Verma, 2009). Table 1 shows details about crop management, cultivars, final grain yield, and dates of planting, harvest, reproductive stage entry, and beginning of physiological maturity.

Site/Year	Crop/Cultivar	Plant Pop. (plants/ha)	Planting DOY	R1 DOY	RF DOY	Harvest DOY	Grain Yield (Mg/ha)
IMS							
2002	S/Asgrow 2703	370,644	140	191	262	282	3.6
2003	M/Pioneer 33B51	84,329	134	206	255	287	14.0
2004	S/Pioneer 93B09	370,644	154	212	274	299	3.4
2005	M/Pioneer 33B51	83,200	122	195	257	291	13.2
2006	S/Pioneer 93M11	370,644	132	195	263	279	3.9
2007	M/Pioneer 31N28	78,708	121	198	259	310	13.2
2008	S/Pioneer 93M11	370,644	134	190	274	284	4.0
2009	M/Pioneer 32N72	81,509	111	203	272	314	14.2
RMS							
2002	S/Asgrow 2703	370,644	140	190	261	284	3.1
2003	M/Pioneer 33B51	64,292	133	204	247	289	7.7
2004	S/Pioneer 93B09	370,644	154	211	260	286	3.1
2005	M/Pioneer 33G66	60,117	122	199	259	291	9.1
2006	S/Pioneer 93M11	370,644	132	192	261	287	3.9
2007	M/Pioneer 33H26X	62,090	121	194	251	305	10.2
2008	S/Pioneer 93M11	370,644	134	196	270	283	3.7
2009	M/Pioneer 33T57	61,777	112	197	257	315	12.0

Table 1: Crop management details and field averaged grain yield for the two field sites during 2002-2009. (M – maize, S – soybeans, R1- date of silking (maize) and beginning bloom (soybean), RF – date of physiological maturity).

The footprints of the IMZ's are not equal in area and thus field-averaged calculations of soil moisture are weighted by Equation 1 below, where w_i is the weight (i.e., fraction of the field represented by the fuzzy classes associated with the i'th IMZ), x is the measured soil moisture in the i'th IMZ and i increases from 1 to n (the total number of IMZs per field):

$$x_{avg} = \Sigma(w_i x_i) \quad (1)$$

Weights were assigned to each IMZ based on the proportional area of the fuzzy class represented. Not all IMZ's had soil moisture at all four depths, with some IMZ's only having it at 10 cm. Thus, soil moisture is only reported at IMZ's with soil moisture at all depths for the sake of consistency.

Prior to this study, soil samples were collected from IMZ's of the two sites and then analyzed in the laboratory for water retention curves and soil parameters, such as bulk density. Saturation (θ_s) values were calculated from bulk density values obtained from the laboratory. Field capacity (θ_{FC}) and wilting point (θ_{WP}) values were determined from moisture release curves obtained from laboratory work and saturated hydraulic conductivity (K_s) was calculated from aforementioned values of θ_{FC}, θ_{WP}, and θ_s using algorithms in Saxton and Rawls (2006).

Results from the IMZs show that θ_s was normally distributed and K_s had a lognormal distribution. Comparisons of mean and standard deviation of θ_s and $\log_{10} K_s$ are given by location and depth (Table 2a) and by IMZ (Table 2b) at IMS and RMS. Soil texture is generally homogeneous throughout the CSP, with several IMZ's having only one soil texture class (silt clay loam) and of all 40 samples (including those from ICM), 32 of them were considered a silt clay loam texture. Other soil textures (or soil classes; silt loam and silty clay) are found throughout the CSP, but only silt clay loam had a large enough sample size to be statistically significant (α =0.05 level). Nevertheless, the silt clay loam means of θ_s and $\log_{10} K_s$, which are 0.482 m^3/m^3 and -0.63 mm/hr, respectively, compare favorably to the means of 0.464 m^3/m^3 and -0.54 mm/hr for θ_s and $\log_{10} K_s$ reported in Cosby et al. (1984).

		θ_s		$\log (K_s)$	
Location and Depth	n Textures	Mean	Std. Dev.	Mean	Std. Dev.
IMS 10 cm	1	0.444	0.007	-2.06	2.23
IMS 25 cm	1	0.485	**0.029**	-0.55	2.18
IMS 50 cm	1	0.471	0.024	-2.13	2.21
IMS 100 cm	1	0.479	0.017	-2.08	2.33
RMS 10 cm	2	0.503	0.023	0.43	1.85
RMS 25 cm	2	0.506	0.008	0.51	1.04
RMS 50 cm	1	0.491	0.021	0.43	1.32
RMS 100 cm	2	0.510	0.025	1.19	1.93

Table 2a. Mean and standard deviation of two soil parameters (porosity and the log of saturated hydraulic conductivity) obtained from lab measurements for 8 location and depth combinations at IMS and RMS.

		θ_s		log (K_s)	
IMZ	n(Textures)	Mean	Std. Dev.	Mean	Std. Dev.
IMS 2	1	0.453	0.025	-1.80	1.86
IMS 5	1	0.464	0.023	-3.41	1.45
IMS 6	1	0.461	0.022	-1.94	2.10
RMS 1	1	0.500	0.009	1.87	0.53
RMS 2	3	0.513	0.030	1.16	1.31
RMS 3	2	0.499	0.018	-0.53	1.38
RMS 5	1	0.496	0.025	0.05	1.38

Table 2b. Mean and standard deviation of two soil parameters (porosity and the log of saturated hydraulic conductivity) over all depths for IMZ's with soil moisture at IMS and RMS. The number of soil textures in a soil profile at a given location is given in the second column from the left.

Previous studies (Gutmann and Small, 2005; Cosby et al. 1984) reported large variation in soil hydraulic parameters (SHP's) existed in other soil databases; thus it was not unexpected that variation (i.e., the standard deviation) in K_s at Mead was sometimes greater within a field or within an IMZ than across the entire study area. However, even with some significant intra- and inter-field variation in SHP's at Mead, IMZ averaged (i.e., over the entire profile at an IMZ) water contents were still well correlated when using all growing seasons of the eight-year study. This was particularly true at RMS where no irrigations were applied and whose data is most heavily utilized in this paper. Field averaged water contents were especially well correlated during the reproductive stages of maize and soybeans with correlation coefficient values of 0.93 and 0.80, respectively. This suggests the average water content data (primarily from RMS) is a fair representation of conditions across the field on a given date in the analysis presented here.

2.3 Soil moisture sensors

Dynamax Theta probes were installed in the spring of 2001 at depths of 10, 25, 50, and 100 cm as part of three IMZ's in ICM and IMS, and four in RMS. The soil moisture probes were installed at a 45° angle orthogonal to the surface at 10 and 25 cm and were installed using the drip loop method at 50 and 100 cm. Soil moisture sensors were always removed at 10 cm and 25 cm for planting and harvest at all sites. Impedance probes contain a waterproof enclosure, sensing head, and a cable. The enclosure has a measurement circuitry and an oscillator, while the sensor head consists of three outer rods that shield an inner rod. The rods act as a transmission line and have an impedance that is dependent on the dielectric constant of the soil. Topp et al. (1980) showed that a linear relationship exists between the volumetric water content and the dielectric constant. Thus, soil volumetric water content (θ) is the standard soil moisture variable in the CSP, and the broader network of sensors across the state as part of the Nebraska Automated Weather Data Network (AWDN; Hubbard et al. 2009; You et al. 2010).

Soil moisture data from the CSP underwent significant quality control before its release. Data were replaced by previous day's values if one day was bad (e.g., sensor issue) and by linear interpolation if more than one day was bad. Meteorological data from the IMZ's were examined for incidence of precipitation prior to use of interpolation. Data classified as questionable after collection sometimes had sensor calibration values manually altered by professional laboratory technicians in cases where the present criterion on formula did not identify bad data. Automated soil moisture measurements were collected hourly and averaged daily over the span of the project.

3.0 Results and Discussion

3.1 Climatology comparison

Weather records started to be collected at Mead, NE in the summer of 1981 and the 30-year climatology used in this study considers the period from 1982-2011. For temporal consistency, the 30-year period of record (POR) chosen at the two High Plains sites (Scottsbluff, NE and North Platte, NE) and at the other Corn Belt sites (Des Moines, IA; Moline, IL; and Fort Wayne, IN) is also 1982-2011. The two High Plains sites were chosen to best exemplify the precipitation gradient across the state of Nebraska. Des Moines, Moline, and Fort Wayne were chosen as respective representatives of the Western, Central, and Eastern Corn Belt because they are at a very comparable latitude to Mead, have similar terrain, are surrounded by intensive maize and soybean production in the growing season, and had a complete period of record (i.e., no missing data gaps). Growing season (hereafter referred to as GS) precipitation, defined as 1 May to 31 October for this study, during this POR at Mead ranged from a low of 315 mm in 1995 to a maximum of 868 mm in 1986. The maximum GS precipitation compared favorably to that of the central and eastern Corn Belt sites, with only Des Moines, IA having a significantly higher total. The minimum GS precipitation value at Mead, NE also compared favorably with that of other Corn Belt sites and was even higher than the minimum value at Moline, IL. Additional information is contained in Table 3.

	Lat	Lon	Elev (m)	Median	Min	Max	10%	90%
Scottsbluff, NE	41.88	-103.59	1205	274	116	483	157	420
North Platte, NE	41.13	-100.70	848	383	229	603	284	508
Mead, NE	41.15	-96.49	354	469	315	868	373	715
Des Moines, IA	41.53	-93.66	287	567	394	1135	427	871
Moline, IL	41.44	-90.51	179	584	254	886	411	822
Fort Wayne, IN	40.98	-85.19	244	539	318	811	388	748

Table 3. Median, minimum, maximum, and the 10^{th} and 90^{th} percentiles of growing season precipitation (mm) during the 30-year period (1982-2011) at all sites. The decimal conversions for latitude (positive for degrees north) and longitude (negative for degrees west) and elevation in meters are given for each location.

However, when one considers the middle of the distribution (i.e., the median) and the broader precipitation distribution (i.e., from 10^{th} percentile to 90^{th} percentile), it illustrates the transitional location of the field sites at Mead between a more consistently wet and sub-humid sites to the east in Iowa, Illinois, and Indiana and the drier, semi-arid climate of the sires in western Nebraska. The median precipitation of 469 mm during the POR at Mead was about 10 mm greater than the minimum precipitation considered necessary for a high-yielding rainfed maize crop (Nield and Newman, 1990). From a probabilistic standpoint, this indicates that a high-yielding maize crop under rainfed conditions will occur a little more than every other year at Mead. In other words, precipitation at Mead is sufficient enough to support decent yielding maize crops without the addition of irrigation. While the probabilities of a high-yielding crop without irrigation are considerably more favorable than Scottsbluff and North Platte where the probabilities of producing high maize without irrigation are 1 in 30 and 1 in 7, respectively, it is notably lower than sites to the east where this probability is a little more than four high-yielding crops out of every five years. Given the relatively sharp gradient in median GS precipitation across the transect from Scottsbluff to Fort Wayne, it is thus not surprising that Mead would be in the transition zone between predominantly rainfed agriculture to the east and predominantly irrigated agriculture to the west as discussed in section 2.1.

Even further evidence of this transition zone is shown in the total July and August precipitation, which could be considered a proxy for precipitation occurring during the critical reproductive stages of maize and soybeans. Mead had a median of 170 mm between July and August (J-A) in the POR and averaged 164 mm during the 8-year study period. The two High Plains sites in Nebraska, Scottsbluff and North Platte, averaged 77 mm and 134 mm, respectively whereas the other Corn Belt sites- Des Moines, IA; Moline, IL; and Fort Wayne, IN averaged 214 mm, 220 mm, and 199 mm in the POR (Table 4). J-A precipitation well exceeded the average of the other Corn Belt sites a total of three times during the 8-year study period and was less than the 30-year average at Scottsbluff in the 2003 flash drought. Thus, soil moisture data from the reproductive stages of maize and soybeans at the Mead CSP site presented in this chapter come from a wide range of precipitation totals: from a typical amount of precipitation in the central and eastern U.S. Corn Belt to a typical amount of precipitation in a semi-arid environment, such as the Nebraska panhandle.

	Median	Max	Min
Scottsbluff, NE	77	164	17
North Platte, NE	134	255	44
Mead, NE	170	332	63
Des Moines, IA	214	558	81
Moline, IL	220	435	63
Fort Wayne, IN	199	353	91

Table 4. Median, minimum, maximum July and August (JA) precipitation (mm) during the 30-year period (1982-2011) at all sites used for the climatology.

Mead is also in a transition zone with respect to the number of days where the maximum temperature is at or above 35°C. Temperatures above 35°C can be detrimental to maize development and yield and thus, frequencies of these higher temperatures at locations are often reported in publications such as the USDA Weekly Weather and Crop Bulletin because of their impact on crop yields. Table 5 shows that the median number of days with temperatures over 35°C at Mead was 9 during the POR, which was less than the 20 days and 16 days at the western Scottsbluff and North Platte locations, but more than the central and eastern Corn Belt sites that generally experienced less than 5 days. There were some GS in the POR where Mead had only handful of days over 35°C with the 1992 GS having no days over 35°C. By comparison, the eastern sites of Moline, IL and Fort Wayne, IN had 6 and 14 GS in the POR without a maximum temperature over 35°C.

	Median	Max	Min
Scottsbluff, NE	20	37	2
North Platte, NE	16	35	2
Mead, NE	9	27	0
Des Moines, IA	4	31	0
Moline, IL	5	27	0
Fort Wayne, IN	1	18	0

Table 5. Median, minimum, and maximum number of days in a growing season during the POR when maximum temperatures equaled or exceeded 35°C.

Precipitation and temperature are both important factors for crop development and final yield determination. Yet, one issue of using only total GS precipitation to predict yield is that it does not necessarily reflect the timing of precipitation during the season. Figure 1 presents accumulated GS precipitation for all eight seasons at Mead. The wettest GS during the study period occurred in 2007 when maize was the common crop at both field sites, but not have the highest maize yield at RMS, which was recorded in 2009. The highest maize yield during a year with significantly less overall GS precipitation than 2007, but the precipitation was received (as shown in Fig.1) at more regular temporal intervals, and in somewhat similar amounts. The 2009 GS was also relatively cool (17.9°C versus the 30-year average of 19.2°C), which when combined with regular rainfall events, allowed soil moisture to be sustained at higher levels during the critical reproductive stage compared to 2007.

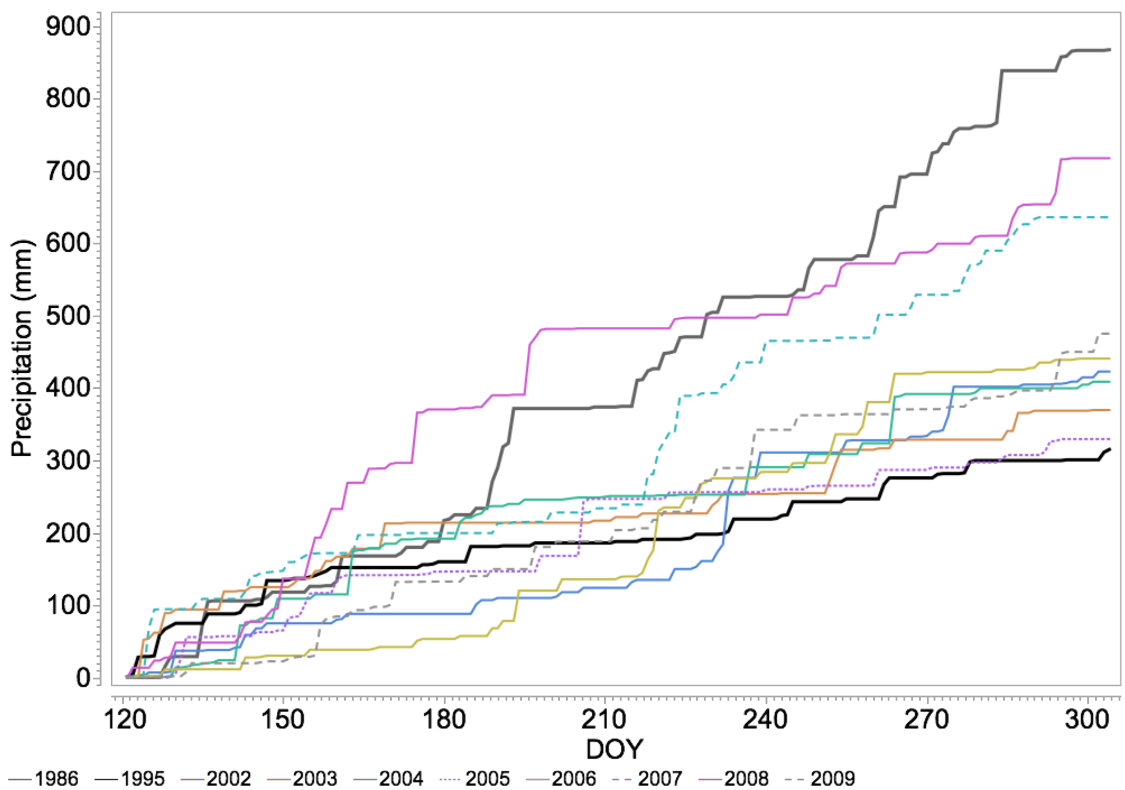

Figure 1: Accumulated precipitation for each season in the study period (2002-2009) and the driest season (1995) in the 30-year period of record and the wettest season (1986) in the 30-year period of record.

Similarly, the driest year during the study period (2005) had a higher overall maize yield (9.1 Mg/ha vs. 7.7 Mg/ha) at RMS than during the “flash” drought year of 2003 (Hunt et al. 2014), which has higher total GS precipitation. Timing was again critical with the vast majority of precipitation in 2003 falling during the early portion of the GS during the vegetative stages of maize, while in 2005 a large precipitation event occurred in late July and another moderate rainfall event in mid-August allowing a recharge of soil moisture during critical reproductive stages of maize.

The previous two paragraphs explained in some detail how varied total GS precipitation during the study period did not necessarily lead to a direct correlation with maize yield. The point of the following sections (and this paper in general) is not for yield prediction or yield correlation based on a few meteorological variables; rather, the following sections will demonstrate how soil moisture reflects inter- and intra- seasonal precipitation differences. In the following sections, shallow depth in-situ soil moisture measurements are shown to be the best reflection of recent climatic conditions (e.g., hot and dry), and deeper soil moisture being the best reflection of longer-term (i.e., 30-60 days) climatic conditions.

3.2 Soil Moisture climatology

Table 6 shows general statistics for soil moisture at RMS during the 8-year study period. As expected, seasonal average water content was lower (higher) in the GS with lower (higher) precipitation. A comparison of the first and second halves of the study period demonstrates this clearly. From 2002 through2005, the average seasonal precipitation was 382 mm and the average water contents were 0.304, 0.331, 0.312, and 0.356 m^3/m^3 at the10 cm, 25 cm, 50 cm, and 100 cm, respectively. The 2005 GS was the driest GS overall and had the lowest average water content at 10 cm and 25 cm depths of any GS in the study period with an average of 0.285 and 0.304 m^3/m^3. The lowest average water content at the deeper depths (i.e., 50 cm and 100 cm) occurred during the 2003 flash drought with an average of 0.285 and 0.334 m^3/m^3 at 50 cm and 100 cm respectively. During the much wetter 2006-2009 period, seasonal precipitation averaged 542 mm and the average water contents were 0.347, 0.352, 0.399, and 0.395 m^3/m^3 at 10 cm, 25 cm, 50 cm, and 100 cm depths. The 2008 GS was the wettest overall with 717 mm of precipitation and also had the highest average soil moisture content at 10 cm and 25 cm of any GS in the study period with an average of 0.377 and 0.367 m^3/m^3 at 10 cm and 25 cm, respectively. The water content at 50 cm (100 cm) was highest in the 2009 GS (2007 GS) with an average of 0.40 m^3/m^3 for both.

Season	Precip (mm)	10 cm	25 cm	50 cm	100 cm	**Days where $\theta < \theta_{50\%}$** 10 cm	50 cm
2002	423	0.31	0.33	0.31	0.37	91	78
2003	369	0.33	0.36	0.29	0.33	70	114
2004	408	0.29	0.33	0.30	0.36	77	110
2005	329	0.29	0.30	0.36	0.36	110	66
2006	440	0.33	0.35	0.39	0.39	62	8
2007	636	0.33	0.35	0.40	0.40	62	13
2008	717	0.38	0.37	0.40	0.40	36	0
2009	475	0.35	0.34	0.40	0.39	30	0

Table 6. Total RMS growing season precipitation, average RMS water content at 10 cm, 25 cm, 50 cm, and 100 cm by season, and the number of days in a season when the water content at 10 cm and 50 cm was such that it was less than 50 percent of available water for the respective depth.

Another way to approximate how dry or moist a GS was is to determine the number of days that soil moisture was below (above) a certain threshold, which was set at 50 percent of available water at the 10 cm and 50 cm depths. This was calculated by determining the midpoint between field capacity and wilting point across the field at RMS, which for both 10 cm and 50 cm was 0.315 m^3/m^3. The

10 cm depth was chosen for further analysis as it had the most dynamic response to precipitation and incipient dry spells. The 50 cm depth was chosen for analysis as it was a better indicator of longer-term dry spells than 10 or 25 cm but was more responsive to short-term precipitation events than at 100 cm. A threshold of 50 percent was selected because this is commonly considered to be the lowest point where evapotranspiration will equal the potential evapotranspiration rate (Waring and Running, 1998) and thus is the point where stress due to a lack of soil moisture could begins to affect the crop.

At 10 cm, the number of days below the threshold ranged from 30 in 2009 to 110 in 2005. The number of days below the threshold at 50 cm followed a similar pattern with a maximum of 114 days during the 2003 flash drought and 0 days in both 2008 and 2009. Thus, the number of days below the thresholds at 10 cm and 50 cm was much lower in years with precipitation amounts above the long-term median and much higher during the years where precipitation was much less than the long-term median. However, total season precipitation was not a perfect predictor of the number of days below the threshold. Timing of precipitation played a large role as well. For example, the 2009 GS was not close to being the wettest year but it had perhaps the most well timed precipitation of any GS in the study period and was easily the coolest, therefore it had less “stress” than any other season.

Timing of the precipitation was an important factor influencing soil moisture conditions. The 2005 GS, though driest, did not have the most days blow the 50% available water threshold at 50 cm because of the aforementioned timing of significant precipitation events in late July and August. The 2006 GS was very dry early as shown by Fig. 1 but had fewer days below the threshold than in the preceding years because of well-timed precipitation in July and August. It could therefore be argued that timing of precipitation in a GS can be almost, if not equally, as important as the total amount of GS precipitation. This assertion is further supported in the remaining subsections.

3.3 Precipitation-Soil Moisture lag

The relationship of precipitation and soil moisture was strong when considering the study period in its entirety, with an R^2 of 0.79 between total precipitation and mean water content over all depths at RMS. But as previous studies documented [e.g., Basara et al. (1998); Illston and Basara (2003)], flash droughts can occasionally occur in GSwith above average precipitation and excessively high temperatures and drying conditions, which can cause severe agricultural impacts. Thus, the timing of precipitation is critical and total GS precipitation may not necessarily reflect a prolonged stretch of dry weather that occurred during a portion of the GS.

Even though precipitation and soil moisture were strongly correlated over the study period, the relationship weakened when comparing mean water content of all soil depths and precipitation over shorter-time scales (e.g., a few weeks) within a GS. This implies that a lag existed between precipitation and soil moisture during the eight years of the study period. To test this, we considered the water content on a given date (e.g., 1 August) and compared it to the previous 14-, 30-, and 60-day precipitation totals to test both the lag and varying time scales of the precipitation-soil moisture lags at varying soil depths.

Table 7 shows that the correlation between soil moisture and precipitation across the GS. In general, strongest relationship was found during the hotter months of July of August with the highest correlations between short-term (i.e., 14-day) precipitation and soil moisture at shallower depths and medium- and longer-term precipitation and deeper soil moisture conditions. This illustrates the tendency for shallow soil moisture to be most affected by short-term dry spells or a single precipitation event and deeper soil moisture to depict the antecedent precipitation conditions on the order of a month(s).

14-day	10 cm	25 cm	50 cm	100 cm
May	0.355	0.304	0.021	0.441
June	0.628	0.498	0.378	0.632
July	0.711	0.643	0.488	0.304
August	0.823	0.795	0.544	0.484
September	0.624	0.633	0.318	0.278
October	0.571	0.401	0.325	0.409
30-day	10 cm	25 cm	50 cm	100 cm
May	0.509	0.490	0.177	0.568
June	0.563	0.420	0.329	0.641
July	0.662	0.706	0.655	0.517
August	0.799	0.805	0.747	0.685
September	0.401	0.532	0.517	0.550
October	0.537	0.483	0.353	0.471
60-day	10 cm	25 cm	50 cm	100 cm
May	0.440	0.478	0.416	0.631
June	0.609	0.520	0.313	0.677
July	0.677	0.705	0.660	0.578
August	0.607	0.719	0.850	0.867
September	0.350	0.407	0.774	0.812
October	0.537	0.373	0.592	0.669

Table 7. Correlation (R) between RMS averaged soil moisture and precipitation over the previous 14 days, 30 days, and 60 days.

Figures 2a-h and Table 8 demonstrate this well with the 2007 season (Figure 2f) is a compelling case study because of a dry spell sandwiched in between wet spells. In 2007, only 2 mm had fallen prior to 1 July at Mead in the previous 14-days and the water content at 10 cm at RMS had fallen below 0.25 m^3/m^3. However, the early portion of the GS had been quite wet (184 mm in May) and the water content at 100 cm was over 0.40 m^3/m^3 and remained at the level until early in the reproductive stage. Thus, the deeper soil moisture was reflective of the wet spring while the shallow soil moisture was reflective of the dryness of the previous few weeks. Significant precipitation returned in early August and immediately brought the field-average water content at 10 cm from 0.21 m^3/m^3 to 0.39 m^3/m^3 over the course of five days. There was also recharge observed at 50 cm and then at 100 cm after the five day wet spell, but the 10 cm depth was certainly more reflective of the short-term wet spell than the deeper depths.

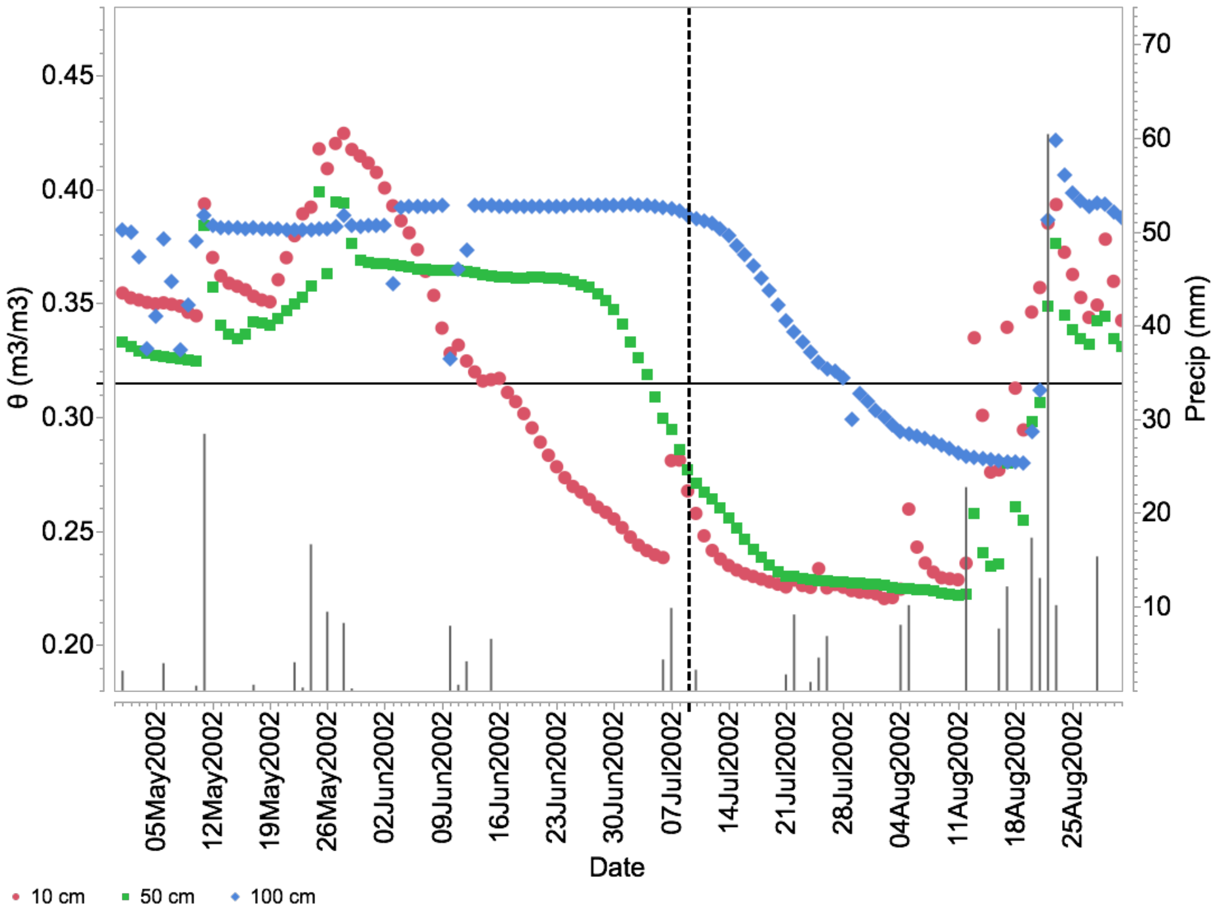

Figure 2a: Water content at 10 cm (red circles), 50 cm (green squares), and 100 cm (blue diamonds) and precipitation totals for a given a day (black needles; see scale on right) from 1 May to 31 August 2002. Vertical dotted line indicates the beginning flower stage of soybeans at RMS in 2002. The solid horizontal line represents a fraction of available soil moisture of 0.5 at the 10 cm and 50 cm depths.

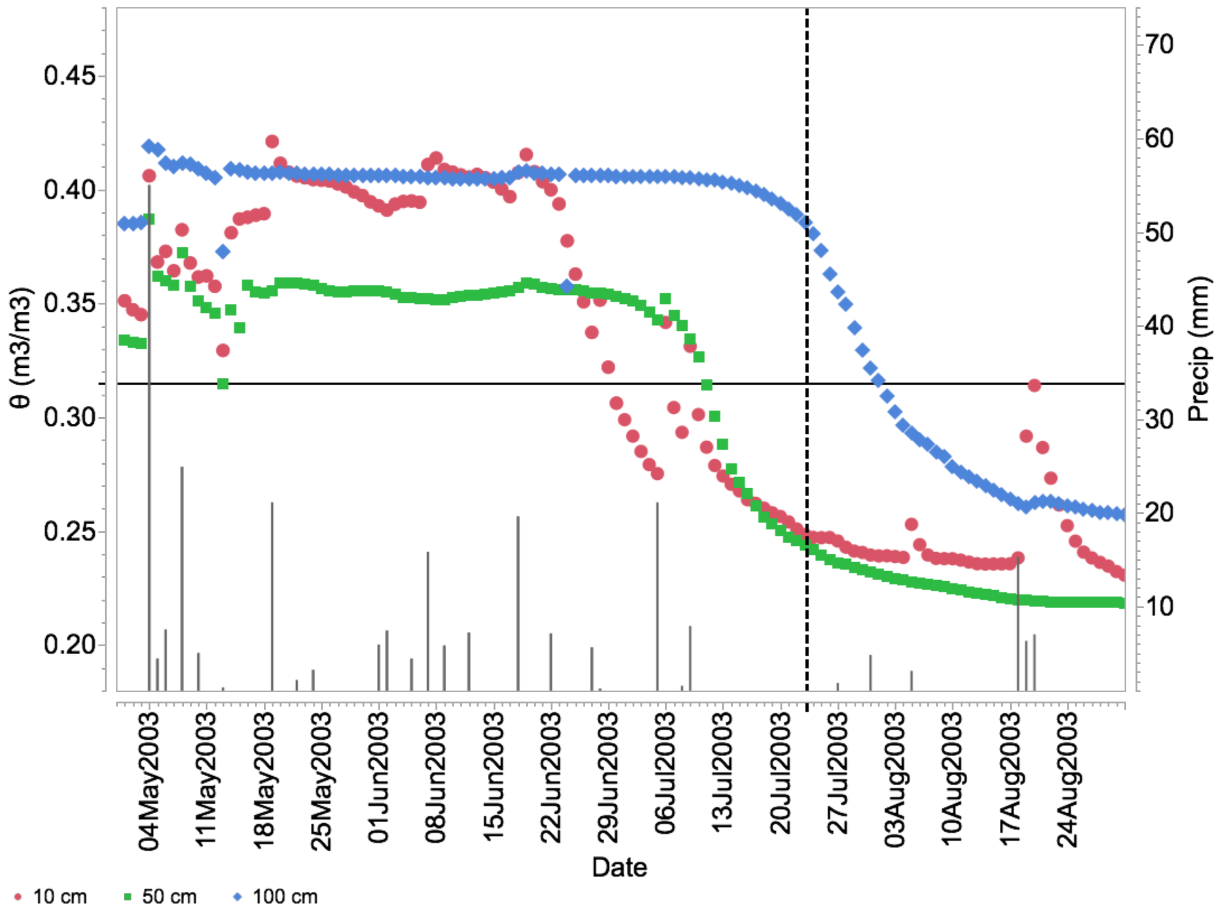

Figure 2b: Water content at 10 cm (red circles), 50 cm (green squares), and 100 cm (blue diamonds) and precipitation totals for a given a day (black needles; see scale on right) from 1 May to 31 August 2003. Vertical dotted line indicates the beginning of silking of maize at RMS in 2003. The solid horizontal line represents a fraction of available soil moisture of 0.5 at the 10 cm and 50 cm depths.

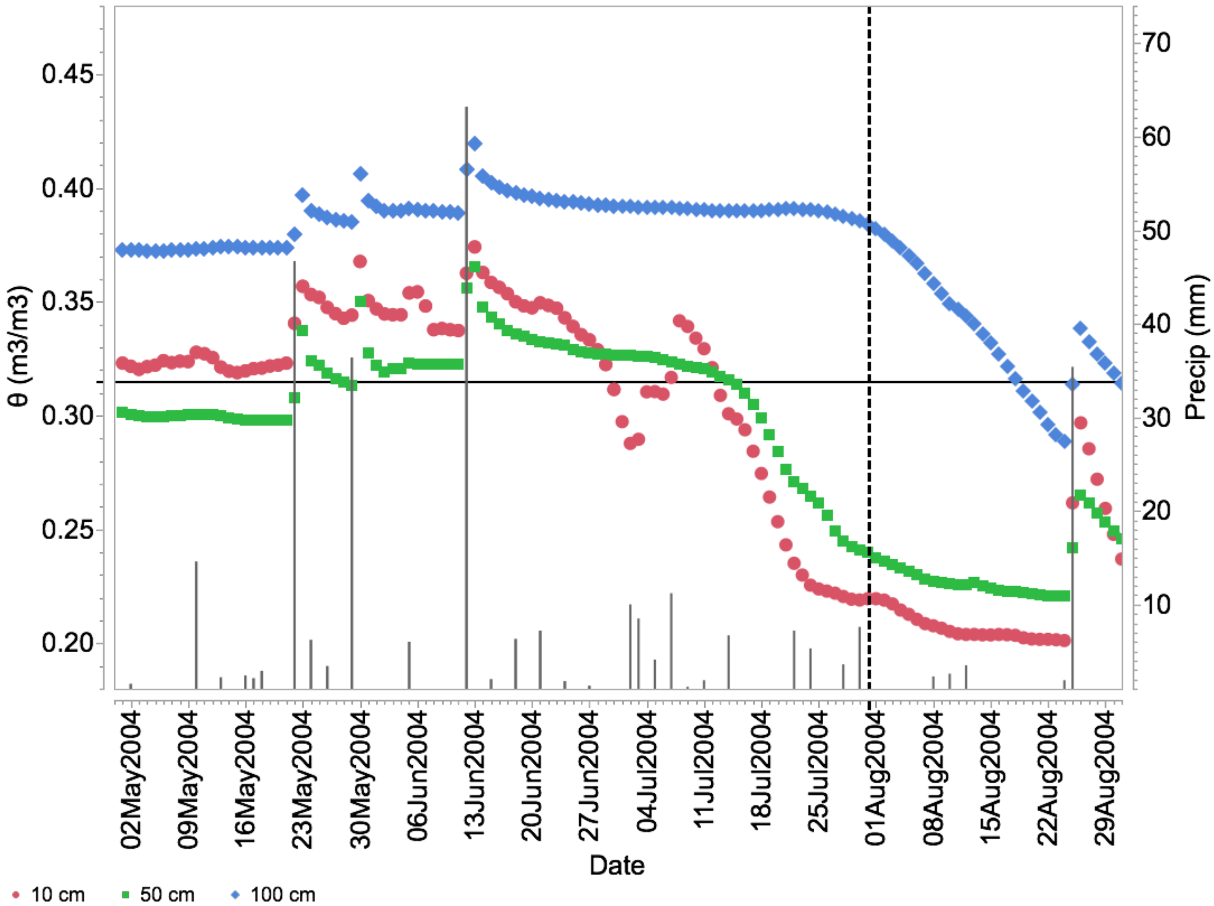

Figure 2c: Water content at 10 cm (red circles), 50 cm (green squares), and 100 cm (blue diamonds) and precipitation totals for a given a day (black needles; see scale on right) from 1 May to 31 August 2004. Vertical dotted line indicates the beginning flower stage of soybeans at RMS in 2004. The solid horizontal line represents a fraction of available soil moisture of 0.5 at the 10 cm and 50 cm depths.

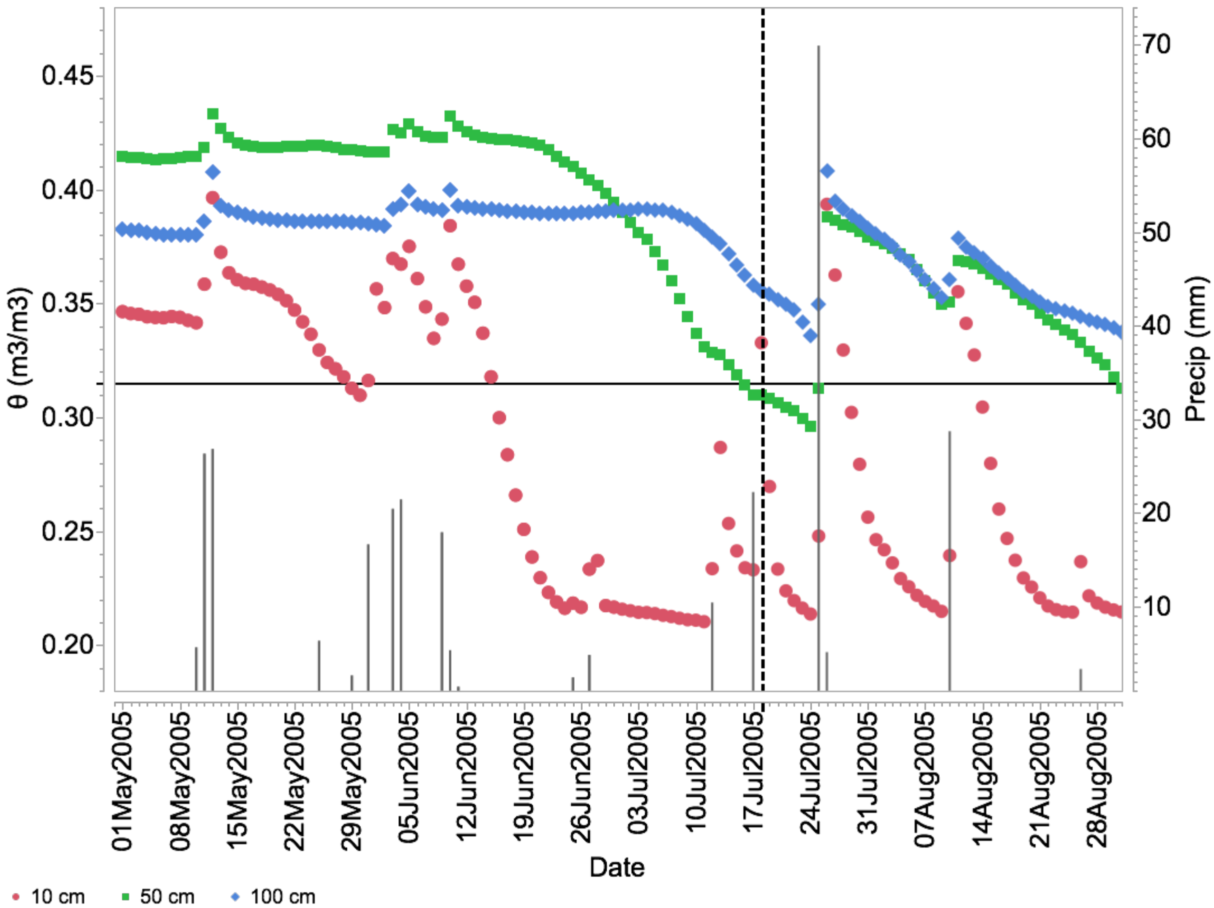

Figure 2d: Water content at 10 cm (red circles), 50 cm (green squares), and 100 cm (blue diamonds) and precipitation totals for a given a day (black needles; see scale on right) from 1 May to 31 August 2005. Vertical dotted line indicates the beginning of silking of maize at RMS in 2005. The solid horizontal line represents a fraction of available soil moisture of 0.5 at the 10 cm and 50 cm depths

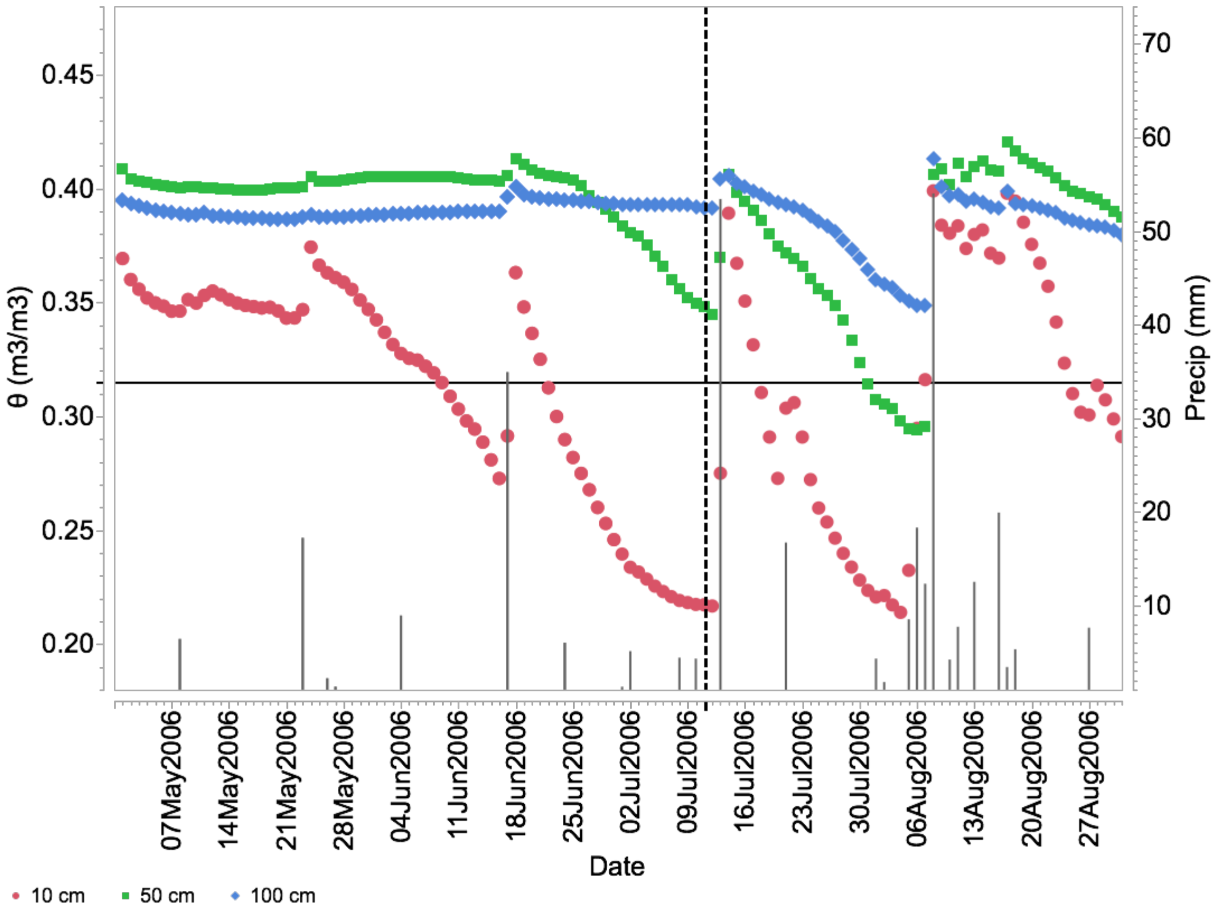

Figure 2e: Water content at 10 cm (red circles), 50 cm (green squares), and 100 cm (blue diamonds) and precipitation totals for a given a day (black needles; see scale on right) from 1 May to 31 August 2006. Vertical dotted line indicates the beginning flower stage of soybeans at RMS in 2006. The solid horizontal line represents a fraction of available soil moisture of 0.5 at the 10 cm and 50 cm depths.

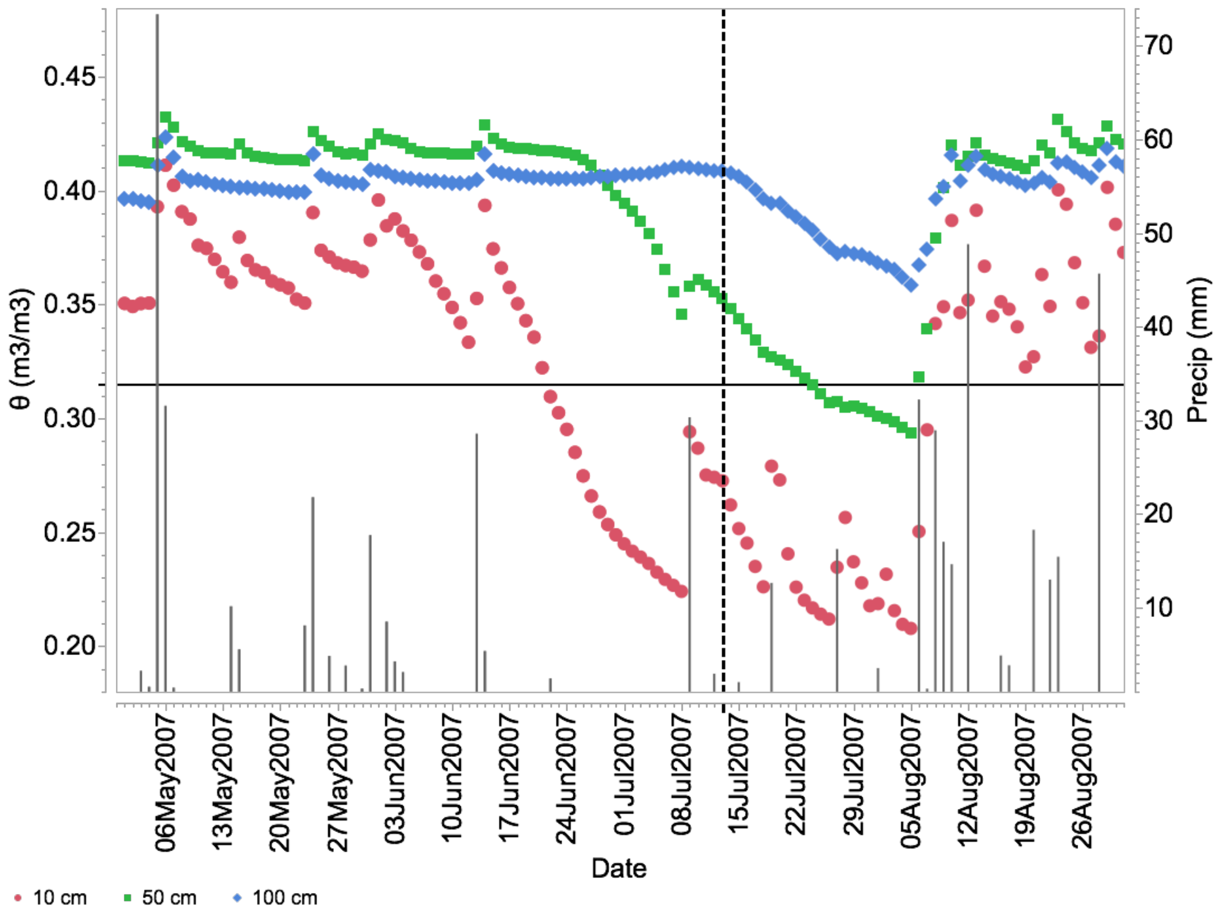

Figure 2f: Water content at 10 cm (red circles), 50 cm (green squares), and 100 cm (blue diamonds) and precipitation totals for a given a day (black needles; see scale on right) from 1 May to 31 August 2007. Vertical dotted line indicates the beginning of silking of maize in 2007. The solid horizontal line represents a fraction of available soil moisture of 0.5 at the 10 cm and 50 cm depths.

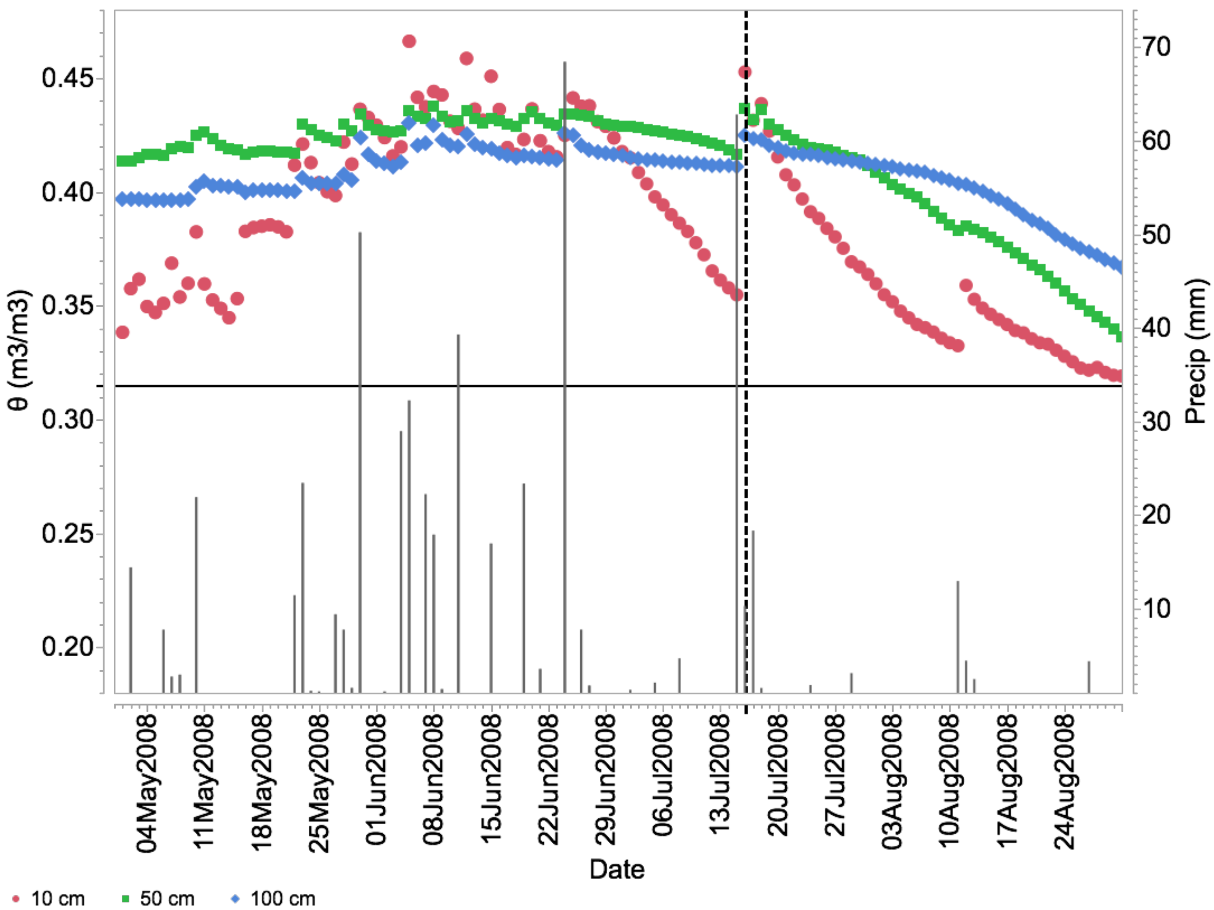

Figure 2g: Water content at 10 cm (red circles), 50 cm (green squares), and 100 cm (blue diamonds) and precipitation totals for a given a day (black needles; see scale on right) from 1 May to 31 August 2008. Vertical dotted line indicates the beginning flower stage of soybeans at RMS in 2008. The solid horizontal line represents a fraction of available soil moisture of 0.5 at the 10 cm and 50 cm depths.

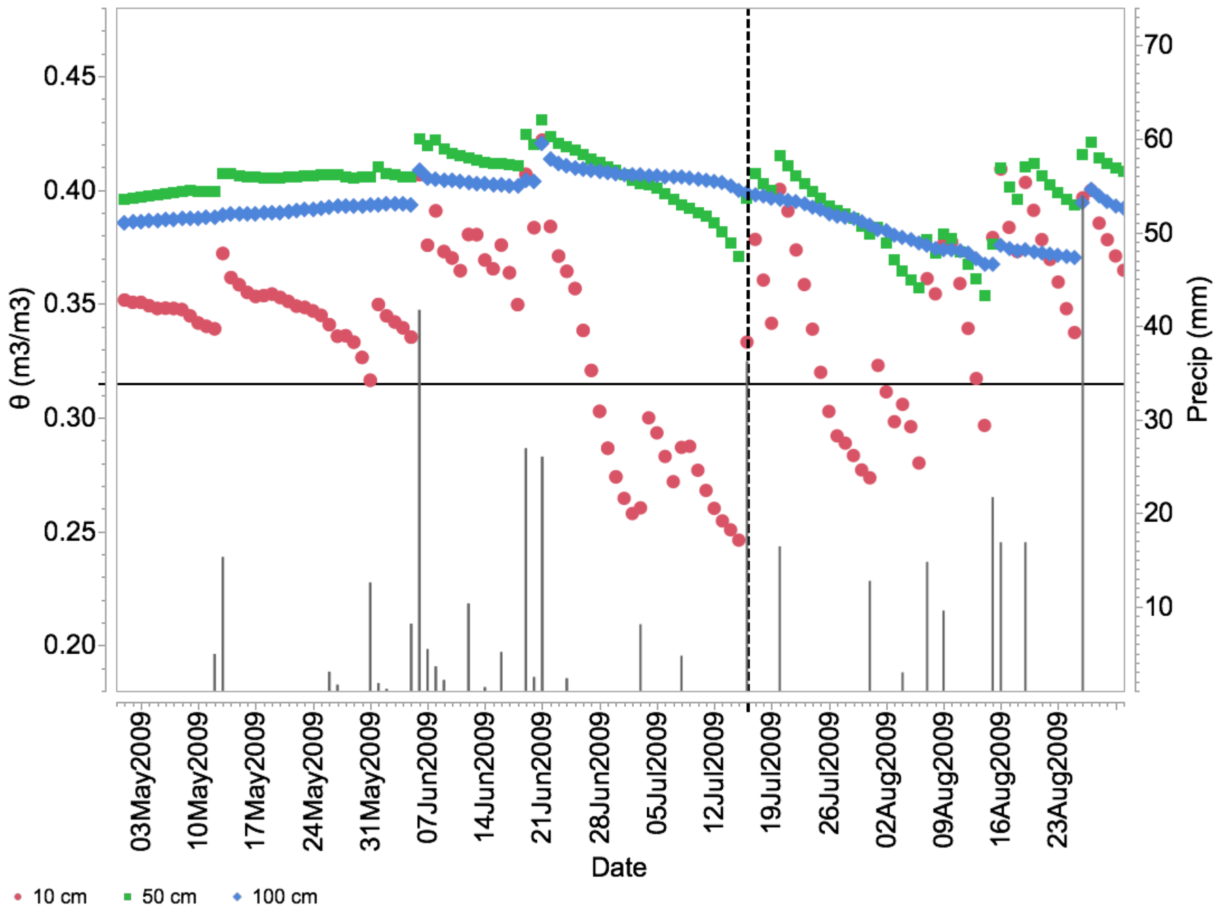

Figure 2h: Water content at 10 cm (red circles), 50 cm (green squares), and 100 cm (blue diamonds) and precipitation totals for a given a day (black needles; see scale on right) from 1 May to 31 August 2009. Vertical dotted line indicates the beginning of silking of maize at RMS in 2009. The solid horizontal line represents a fraction of available soil moisture of 0.5 at the 10 cm and 50 cm depths.

Total Precipitation (mm)			
Season	14-day	30-day	60-day
2002	0	20	96
2003	34	67	213
2004	16	88	210
2005	8	74	159
2006	7	52	***80***
2007	2	51	235
2008	104	**265**	**405**
2009	57	136	177

Table 8. Total antecedent precipitation in the 14, 30, and 60 days prior to 1 July at Mead, NE in each season during the study period. Values in bold (bold italics) represent precipitation amounts that were a maximum (minimum) when considering the 30-year period of record.

Another interesting example is the 2002 GS (Figure 2a) where considerably dry conditions were abruptly halted in late August by significant precipitation. In 2002, less than 100 mm of total rainfall was received in May and June combined (compared to an average of 212 mm), and the water content at both 10 cm and 50 cm fell below 0.25 m^3/m^3 by early July. The water content at both depths remained around this minimum for most of July and the first half August. The decline to that level happened at 10 cm first followed a few weeks later at 50 cm. The decline at 100 cm from a moist 0.40 m^3/m^3 began once soil moisture had become depleted from the shallower depths. Higher precipitation returned over the last half of August and was observed in the soil moisture first at 10 cm with the first precipitation event on 12 August, a week later at 50 cm with additional precipitation, and finally at 100 cm on 23 August after 100 mm of precipitation fell over a four-day period.

3.4 Precipitation-Soil moisture paradox

Even though soil moisture and precipitation were strongly correlated over a season as shown for the rainfed RMS, the amount of water applied by irrigation at IMS in a given year had almost low correlation to total season precipitation. This was partly because irrigation applications were generally lower in years soybeans were planted than in years with maize (Table 9), as soybeans were generally not irrigated until the later beginning bloom (R1) reproductive stage compared to maize that often needs irrigation earlier during the later half of the earlier vegetative stage. However, timing of precipitation and soil moisture status were more important to irrigation management than the crop type at IMS and the total antecedent precipitation at a given point in the season. The season with the fewest number of irrigation applications was not the wettest entire GS during the study period (2008), but the year with the lowest combined May-June (MJ) precipitation in 2006.

Season	Crop Type	Precipitation (mm)	Irr. Treatments	Irrigation (mm)
2002	S	423	6	209
2003	M	369	11	347
2004	S	408	5	159
2005	M	329	9	302
2006	S	440	4	122
2007	M	636	8	265
2008	S	717	7	251
2009	M	475	6	198

Table 9. Total growing season precipitation (mm) at RMS, the number of irrigation treatments, and total irrigation amount applied (mm) over the eight growing seasons at IMS. For crop type, S= soybeans and M= maize.

This paradox is best explained with some background about these two highlighted GS. The 2006 GS had the driest start (i.e., MJ period) in the POR and the 2008 GS was the wettest (refer to Fig. 1). Overall, precipitation in 2006 was a little below the median, while 2008 was one of the wettest GS in the POR. It would typically be assumed that the amount of water applied by irrigation in 2006 would far be exceeded the amount applied in 2008. However, the opposite was true with the2006 GS having the fewest irrigation applications of any year in the study period, while the 2008 season had the most irrigation applications of any year planted to soybeans, including the 2002 drought year.

Figure 2e shows these differences between these two years for the IMS. During the 2006 GS, timely precipitation in July prevented significant depletion at the deeper the 50 cm and 100 cm depths at both RMS and IMS. Then, frequent precipitation in August allowed for significant moistening at all depths at RMS and negated the necessity of frequent irrigation applications at IMS.

Conversely, the only dry spell during the entire 2008 GS occurred during a critical time (i.e., August) for soybeans. Even though the dry spell did not lead to a significant decline in soil moisture at 50 cm and 100 cm, the depletion of soil moisture in the shallow part of the profile necessitated the need for irrigation treatments, as there were concerns about root depths potentially being more shallow than normal because of the abnormally wet spring. Thus, frequent irrigation applications were necessary in 2008, in spite of the wet GSoverall.

4.0 Summary and Conclusions

Eight years of soil moisture and climatological data from the CSP at Mead, NE revealed unique results from a location situated in a transition zone between predominantly rainfed agriculture to the east and predominantly irrigated agriculture to the west. The eight years at Mead featured total precipitation for May and June in 2008 that would have been the wettest common period at the Eastern Corn Belt site of Fort Wayne, IN. It also featured total precipitation for July and August in 2003 that was lower than the common period average at the semi-arid, western High Plains site of Scottsbluff, NE. Thus, climatological extremes for both the wet end and dry conditions across this broader east-west expanse across the U.S. Great Plains and Corn Belt were realized at Mead during the eight-year study period, even though the average precipitation during the study period at Mead was close to the 30-year median.

During the first half of the study period (2002-2005), there were prolonged periods in all four GS where the soil moisture content was below the 50 percent of available water threshold at both 10 cm and 50 cm depths. This lack of root-zone soil moisture had a detrimental impact on yields at the rainfed site (RMS) compared to the irrigated site (IMS), especially during the flash drought of 2003 when the maize yield at RMS was less than half of the IMS. These four early GS demonstrated the benefit of having irrigation at Mead and the necessity of it in a semi-arid environment where GS conditions are typically like those in the first half of the study period in this research.

Conversely, the latter half of the study period was generally wetter than average. Precipitation at Mead was not only higher in sum over those years, but was also more regularly distributed, resulting in the average soil moisture content being much higher than the earlier part of the study period. Drier periods did occur in the second half of the study period and soil moisture stress was expressed in the top depth, but typically had minimal effects on the deeper depths. The magnitude of stress tended to be lower and the duration much shorter during these years. As a result, irrigation treatments were less numerous at IMS and yields at RMS were closer to those of IMS, particularly in 2009 (maize) when there were no days of stress at 50 cm and in 2006 when significant precipitation was well-timed during the reproductive cycle of the soybean crop.

The results obtained during this study period showed the importance of the timing of precipitation and soil moisture response, particularly for irrigation scheduling at IMS. The years with the fewest irrigation application for both maize and soybeans were not the wettest years during the study period. Paradoxically, the year with the fewest irrigation treatments when soybeans were the common crop between RMS and IMS was in 2006, which had below average GS precipitation. The year with the most irrigation treatments when soybeans were also the common crop in 2008 was one of the wettest seasons in the 30-year POR. The primary difference between the below average 2006 GS and the wet 2008 GS was that precipitation fell at regular intervals during critical reproductive stages for soybeans in 2006 keeping the soil profile moist. Conversely, the only dry spell of the 2008 GS occurred during that same critical period, thus necessitating irrigation applications that prevented depletion of the top half of the soil profile at IMS.

For GS where maize was the common crop, the wettest GS (2007) did not have the highest averaged soil moisture or the highest yields at RMS. That distinction belonged to the 2009 GS, which was only slightly above the 30-year median. Again, timing of the rains was the key difference with a large share of the precipitation occurring early in the season for 2007 and again late in the summer and autumn. Both of these time spans were outside the critical reproductive period for maize that determines the crop’s final yield. During the 2009 GS, most rainfall occurred during these critical stages for maize, keeping the soil profile moist and achieving higher yields than might be expected when total annual precipitation was only slightly above the 30-year median. Thus, the old adage that timing is everything, certainly has a strong element of truth to it when it comes to precipitation, soil moisture, and crop production in this study.

As shown and discussed previously in this chapter, soil moisture under crop cover is highly dependent on the amount of precipitation. Soil moisture, on average, was higher at all depths in the later years of the study when precipitation was more plentiful. Timing of precipitation was important too and as in the case of the 2007 and 2008 growing seasons, abnormally wet seasons can have dry spells long enough in duration to require a number of irrigation treatments, particularly if the only dry spell in a season coincides with the most critical time for a crop. In areas where irrigation is a necessity for high-yielding crops and groundwater resources are becoming more limited, knowledge of soil moisture allows producers to make smart decisions about when to irrigate.

For example, knowing the crop could go another few days before an irrigation could save a lot of money and water if the decision to wait a few days based on soil moisture data if a significant precipitation event materialized. Soil moisture is not perfectly correlated with crop yield, because other external factors (i.e., non-agroclimatological) can have a significant impact. However, soil moisture data can help fill in the knowledge gap as to the effectiveness of precipitation events and if assimilated properly into crop models or land models coupled with crop models, it is quite likely that uncertainty in yield projections could be reduced.

5.0 Acknowledgements:

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CHAPTER 3: THE DYNAMIC RELATIONSHIP BETWEEN SOIL MOISTURE AND BIOPHYSICAL MEASUREMENTS

Abstract:

The purpose of this chapter is to show the relationship between in-situ soil moisture from a rainfed field and biophysical measurements at a rainfed and nearby irrigated field. Soil moisture sensors were installed at four depths (10 cm, 25 cm, 50 cm, and 100 cm) in Intensive Management Zones (IMZ's) for the purpose of determining crucial plant-soil water relationships under maize and soybeans, both irrigated and rainfed, as part of the Carbon Sequestration Project (CSP) at Mead, NE. The eight years (2002-2009) of soil moisture data utilized in this study captured a range of different growing season conditions, from drought and flash drought to significantly above-average precipitation. This chapter shows that biophysical measurements, such as evapotranspiration and gross primary productivity, had a dynamic response to soil moisture. During the drier seasons, this chapter shows evidence that implies stomatal conductance was negatively affected by soil water stress with direct comparisons of evapotranspiration and gross primary productivity at the irrigated and rainfed field. Ten-day averaged ratios of available energy partitioned to latent heat between the rainfed and irrigated field showed that the rainfed field was sensitive to moderate levels of water stress during peak photosynthesis potential (i.e., the midday hours) and was sensitive to high levels of water stress during the entire day during periods of water stress. This chapter also demonstrates that timing of precipitation is crucial and that above average precipitation in a season doesn't preclude periods of soil water stress if a dry period is sandwiched between wet periods.

1.0 Introduction

This chapter presents unique results obtained from eight years of soil water and biophysical measurements under a rainfed and irrigated agroecosystem. Soil water is an integral part of the hydrologic cycle and a critical parameter for plant growth and development. The previous chapter in the series demonstrated the importance and the growing demand for in-situ soil water measurements. Biophysical measurements, such as evapotranspiration, are an important link between soil moisture and the lower boundary layer of the atmosphere. That link between soil moisture and biophysical measurements under crop cover is the focus of this chapter.

Since its inception in 2001, research from the ongoing CSP at Mead, NE has made outstanding contributions to the understanding of carbon and energy balance over irrigated and rainfed maize and soybeans. In Suyker et al. (2004), the authors presented results of net ecosystem CO_2 exhange (NEE) and gross primary productivity (GPP) during the first year (2001) of the CSP. A dry and hot spell in the middle of that growing season reduced leaf area index (LAI) and NEE at the rainfed maize soybean rotation (RMS) compared to the irrigated maize soybean rotation (IMS).

Verma et al. (2005) reported that GPP was almost twice as high in a maize season as in a soybean season and that net ecosystem production (NEP) was about the same in the rainfed and irrigated field, as increased respiration in irrigated fields with higher soil moisture offset the higher GPP at the irrigated sites compared to RMS. Suyker and Verma (2009) showed that growing season ET accounted for an average of 84 and 72 percent of the annual evaporation at the irrigated sites (ICM, IMS) and RMS respectively. As expected, annual ET was higher at the irrigated sites than at RMS, particularly during the flash drought that occurred during the 2003-2004 season, and was higher in maize years than in soybean years at both IMS and RMS. The authors also showed that the crop coefficient (Kc), which is calculated as the ratio of ET to reference ET (ET_o), was as much as 30 percent higher at IMS than at RMS during the middle of the 2003 flash drought.

Suyker and Verma (2010) showed that the seasonal distributions of GPP were consistent in maize and soybeans throughout the six seasons and that GPP was consistently higher in the irrigated fields than at IMS. This was especially true in the 2003 growing season when cumulative GPP was reduced by 24 percent at RMS compared to IMS. Suyker and Verma (2012) further added that green leaf LAI was a dominant factor in explaining interannual variability of GPP in maize. As also shown in earlier results, mean annual GPP of soybeans was significantly less than that of maize (Suyker and Verma 2010).

The CSP is comprised of three field sites under three distinct cropping systems: 1) irrigated, continuous maize, 2) an irrigated, maize-soybean rotation, and 3) a rainfed maize-soybean rotation. Each field has multiple intensive management zones (IMZ's) where soil water, soil temperature, and other agroecological variables are measured. Soil water, ET, and GPP are among the state variables measured hourly during the eight years (2002-2009) of this study.

2.0 Materials and methods

2.1. Carbon Sequestration Project study site

The CSP is located at the University of Nebraska-Lincoln (UNL) Agricultural Research and Development Center in Saunders County, Nebraska near the town of Mead. This location is roughly 35 km northeast of Lincoln, NE and is defined in Chapman et al. (2001) as being at the western edge of the Western Corn Belt Plains ecoregion. As discussed in Hunt et al (in press), the Mead CSP study site is situated in an area that is a sharp transition zone from predominantly rainfed to predominantly irrigated agroecosystems. Maize and soybeans are the main crops grown in the area.

The CSP commenced in the spring of 2001 and consists of three sites. The first agroecosystem is an irrigated, continuous maize (ICM) site centered at 41˚09'54.2" N, 96˚ 28'35.9" W with an irrigated area of 48.7 ha. The second agroecosystem is an irrigated, rotated maize-soybean (IMS) site centered at 41˚09'53.5" N, 96˚ 28'12.3" W with an irrigated area of 52.4 ha. Both ICM and IMS were irrigated rotations of maize and soybeans under no-till in the ten years prior to the initialization of the CSP. The third agroecosystem is a rainfed, rotated maize-soybean (RMS) site centered at 41˚10'46.8" N, 96˚ 26'22.7" W with an area of 65.4 ha. Prior to the CSP, RMS had 2-4 ha plots of maize, soybeans, wheat, and oats with tillage (Verma et al. 2005). ICM was not considered in this analysis as its management practice (i.e., continuous maize) made it less comparable to RMS than IMS.

Each CSP site consists of six, 20 m x 20 m intensive management zones, hereafter referred to as IMZ's, where detailed process-level studies of soil water, soil carbon dynamics, canopy and soil gas exchange, crop growth and biomass partitioning are established. Further site details are contained in Hunt et al. (2014) and Suyker and Verma (2009).

2.2 Eddy covariance flux method and measurement

Toward the middle of each field is an eddy covariance tower installed for measurements of CO_2 and H_2O fluxes .The eddy covariance method is used to measure the exchange of CO_2 and H_2O between the biosphere and atmosphere at over a hundred sites worldwide and has produced defensible estimates of carbon exchange. The method works by sampling atmospheric turbulence to determine the net difference of material going across the atmosphere-canopy interface (Baldocchi et al. 1988; Baldocchi, 2003). This is accomplished by using Reynolds rules of averaging for the instantaneous mass flux density (Eqn. 1):

$$F = \rho a * \overline{w'c'} \tag{1}$$

where F is the vertical mass flux density, ρ_a is the air density, w is the covariance between fluctuations in vertical velocity, and c is the CO2 mixing ratio.

CO_2 fluxes were measured with an array of sensors- a three-dimensional sonic anemometer (R3, Gill Instruments Ltd., Lymington, UK) and a closed-path

CO_2/H_2O system (LI 6262, Li-Cor Inc., Lincoln, NE) . H_2O fluxes were measured with an open-path CO_2/H_2O sensor (LI 7500, Li-Cor Inc., Lincoln, NE). Further details are given in Verma et al. 2005 and Suyker et al. 2003. Eddy covariance sensors were mounted at a height of 3.0 m above the ground until canopy height exceeded 1.0 m. When the canopy height of maize exceeded 1.0 m, the eddy covariance sensors were moved to a height of 6.0 m, a height they remained at until harvest.

The CO_2 storage in the layer below the eddy covariance sensors was calculated from CO_2 concentration profile measurements and added to the measured CO_2 flux to obtain the net ecosystem exchange (NEE). Estimates of daytime ecosystem respiration were obtained from the night-NEE relationship, which is explained further in Xu and Baldocchi, 2004. The gross primary productivity (GPP) was obtained by taking the difference of NEE and ecosystem respiration. All GPP values in this paper represent a daily average in units of g $C/m^2/d$.

2.3 Soil moisture sensors

Dynamax Theta probes were installed in the spring of 2001 at depths of 10, 25, 50, and 100 cm as part of three IMZ's in IMS and four in RMS. Soil moisture sensors at 10 and 25 cm were removed from all IMZ's during planting and harvest periods and then reinstalled in the same location.

The soil moisture probes were installed at a 45° angle from vertical to the surface at 10 and 25 cm and were installed using the drip loop method at 50 and

100 cm. Theta probes contain a waterproof enclosure, sensing head, and a cable. The enclosure has a measurement circuitry and an oscillator, while the sensor head consists of three outer rods that surround an inner rod. The rods act as a transmission line and develop an impedance that is dependent on the dielectric constant of the soil. Topp et al. (1980) showed that a linear relationship exists between the volumetric water content and the dielectric constant. Thus, soil volumetric water content (θ) is the standard soil water variable in the CSP, as in the Nebraska AWDN (Hubbard et al. 2009; You et al. 2010).

Soil water data from the CSP underwent significant quality control before its release. Data that were classified as questionable were replaced by previous day's values if only one day was bad and by linear interpolation if more than one day was bad. Meteorological data from the IMZ’s were examined for incidence of precipitation prior to use of interpolation. Automated soil moisture measurements were collected hourly and averaged daily over the span of the project.

2.4 Soil water calculations

Each field only has one eddy covariance tower and thus, only one set of biophysical measurements; the nature of these measurements leads to their representation of a footprint. It is therefore necessary to scale up soil water measurements from point values to aerial values before comparisons can be made with ET and GPP. The footprints of the IMZ’s are not equal in area and thus field-averaged calculations of soil water are weighted by Equation 2 below, where w_i is the weight (i.e., fraction of the field represented by the fuzzy classes associated with the i'th IMZ), x is the measured soil water in the i'th IMZ and i increases from 1 to n (the total number of IMZs per field). Weights were assigned to each IMZ based on the proportional area of the fuzzy class represented.

$$\bar{x} = \sum_{i=1}^{n} w_i x_i \tag{2}$$

Prior to the study, soil samples were collected from all IMZ's at the three sites and were analyzed in the laboratory for soil type and water holding capacity. Silt clay loam is the predominant soil texture at IMZ's in both fields. Field capacity and wilting point values at the three sites were determined by averaging the -1/3 bar values and the -15 bar values respectively from moisture release curves determined in the laboratory.

2.5 Potential evapotranspiration calculations

Potential evapotranspiration (ET_p) was calculated for a reference alfalfa crop using an updated version of the Penman-Monteith equation (Monteith, 1965) outlined in Allen et al. (1998). While this method of calculating ET_p underestimates evapotranspiration of a tall maize crop, it allowed for consistent comparisons of ET_p across and between seasons and between RMS and IMS and for direct comparisons with previously published studies. As with other variables, ET_p was calculated and summed over ten-day periods at both RMS and IMS.

2.6 Development stages and period definitions

The dates of specific development stages of maize were determined from records collected during regular field observations of growth throughout the available years of the CSP. There was usually a slight variation in a development stage within a field, so the date listed for a particular development stage of maize is a date when approximately 50 percent of the field was at that stage. LAI measurements were made periodically during a season at various locations and numbers shown in the study are field averages.

As in chapter 2, the growing season (GS) is defined as 1 May to 31 October. However, a majority of this chapter focuses on analysis from a common 90-day period (DOY 151-240) in each season. This common 90-day period (C90) was chosen as it encompasses almost all of the critical stages of a maize plant, from early vegetative to late in the reproductive stage. In this case, maize was roughly at 4-leaf (V4) in every GS at DOY 151 and at the denting stage (R5) at DOY 240.

This chapter also looks more in-depth in a window ranging from 10-days prior to the onset of silking to 20-days subsequent. According to various reports (Elmore 2012), maize is most vulnerable to water stress from just before silking (R1) to the milk stage (R3). Thus, additional focus was given to this 31-day period.

3.0 Results and Discussion

The following section presents an analysis of the relationship of biophysical variables and soil water over four seasons in which maize was the common crop at both RMS and IMS. Of the four seasons in the study period, two were drier than the long-term average of approximately 470 mm for the GS and 280 mm for the C90. In both of seasons, total precipitation was greatly exceeded by total evapotranspiration (ET) and potential evapotranspiration (ETp) during the C90. The other two seasons were wetter than the long-term average and total precipitation exceeded ET and in 2009, precipitation equaled ETp. While there were unifying themes across all four seasons, there are some unique similarities and differences between the two wet (dry) seasons. The remainder of this section is thus dedicated to that.

3.1 Dry seasons

The 2003 GS and 2005 GS were both drier than average and had final maize yields at RMS that were much lower compared to those at IMS (Table 1). According to chapter 2, total GS precipitation at RMS was well below the long-term average in both seasons, with 369 mm and 329 mm in 2003 and 2005 respectively. During the C90 analyzed for this chapter, a total of 150 and 234 mm of precipitation fell in 2003 and 2005 respectively. While both seasons had prolonged dry spells that were detrimental to maize development, the timing of significant water stress and the manifestations of water stress were quite different.

Site/Year	Crop/Cultivar	Plant Pop. (plants/ha)	Planting DOY	R1 DOY	RF DOY	Harvest DOY	Grain Yield (Mg/ha)
IMS							
2003	M/Pioneer 33B51	84,329	134	206	255	287	14.0
2005	M/Pioneer 33B51	83,200	122	195	257	291	13.2
2007	M/Pioneer 31N28	78,708	121	198	259	310	13.2
2009	M/Pioneer 32N72	81,509	111	203	272	314	14.2
RMS							
2003	M/Pioneer 33B51	64,292	133	204	247	289	7.7
2005	M/Pioneer 33G66	60,117	122	199	259	291	9.1
2007	M/Pioneer 33H26X	62,090	121	194	251	305	10.2
2009	M/Pioneer 33T57	61,777	112	197	257	315	12.0

Table 1: Crop management details and field averaged grain yield for IMS and RMS during seasons where maize was the common crop. R1 indicates the day of year of silking and RF indicates the day of year of physiological maturity.

In 2003, the first third of the C90 featured regular precipitation, moist soils, and comparable daily ET rates and daily accumulation of GPP as at IMS. At DOY 180, soil water content at RMS was safely above 0.315, which was defined in chapter 2 as the water content equivalent to the 50 percent available water threshold ($\theta_{50\%}$) at both 10 cm and 50 cm. Total ET and GPP accumulations at that point were 87 mm and 184 g C/m^2, which compared favorably to total ET and GPP accumulations of 93 mm and 194 g C/m^2 respectively at IMS.

The remainder of the season was excessively dry at RMS, especially during the highly sensitive period around silking. In the 31-day window around silking, which began at DOY 194 and ended at DOY 224, only 10 mm of precipitation fell and all possible days had a field average soil water content less than $\theta_{50\%}$. Deficient soil water at RMS led to water stress of the maize crop, which could be inferred in comparing the accumulation of biophysical variables at RMS to those at IMS. During the 31-day window, ET accumulations were 28 mm higher at RMS than at IMS, even though the total ETp was almost identical (Table 2).

	IMS Totals: Critical Period				**Days where $\theta < \theta_{50\%}$**	
Season	Precip + Irr	ET	ETp	GPP	10 cm	50 cm
2003	215	167	142	736	0	0
2005	253	176	146	674	0	0
2007	243	164	146	704	0	0
2009	112	137	135	717	0	0
	RMS Totals: Critical Period				**Days where $\theta < \theta_{50\%}$**	
Season	Precip	ET	ETp	GPP	10 cm	50 cm
2003	10	139	140	633	31	31
2005	108	154	143	579	27	10
2007	67	136	145	609	31	10
2009	73	135	133	689	20	0

Table 2. Total precipitation (with irrigation at IMS), evapotranspiration (mm), potential evapotranspiration (mm), and gross primary productivity (g C m^{-2}) at IMS and RMS over a 31-day period ranging from 10-days prior to silking to 20 days following silking.

Figure 1 shows this in more detail. Daily ET and GPP accumulation rates were quite comparable between IMS and RMS in the first third of the C90 (June-August). However, as soil water deficits became established around silking, accumulation rates at the two sites began to diverge. By the end of the C90, the difference in accumulated ET was 64 mm (418 mm at IMS vs. 354 mm at RMS) and the difference in accumulated GPP was 210 g C/m^2 (1518 g C/m^2 at IMS vs.

1308 g C/m^2 at RMS). Water stress was also evident in the LAI. During the 2003 flash drought, the LAI at RMS began to decline after silking, whereas the LAI at IMS remained steady for the remainder of C90 after peaking at the end of the vegetative stage.

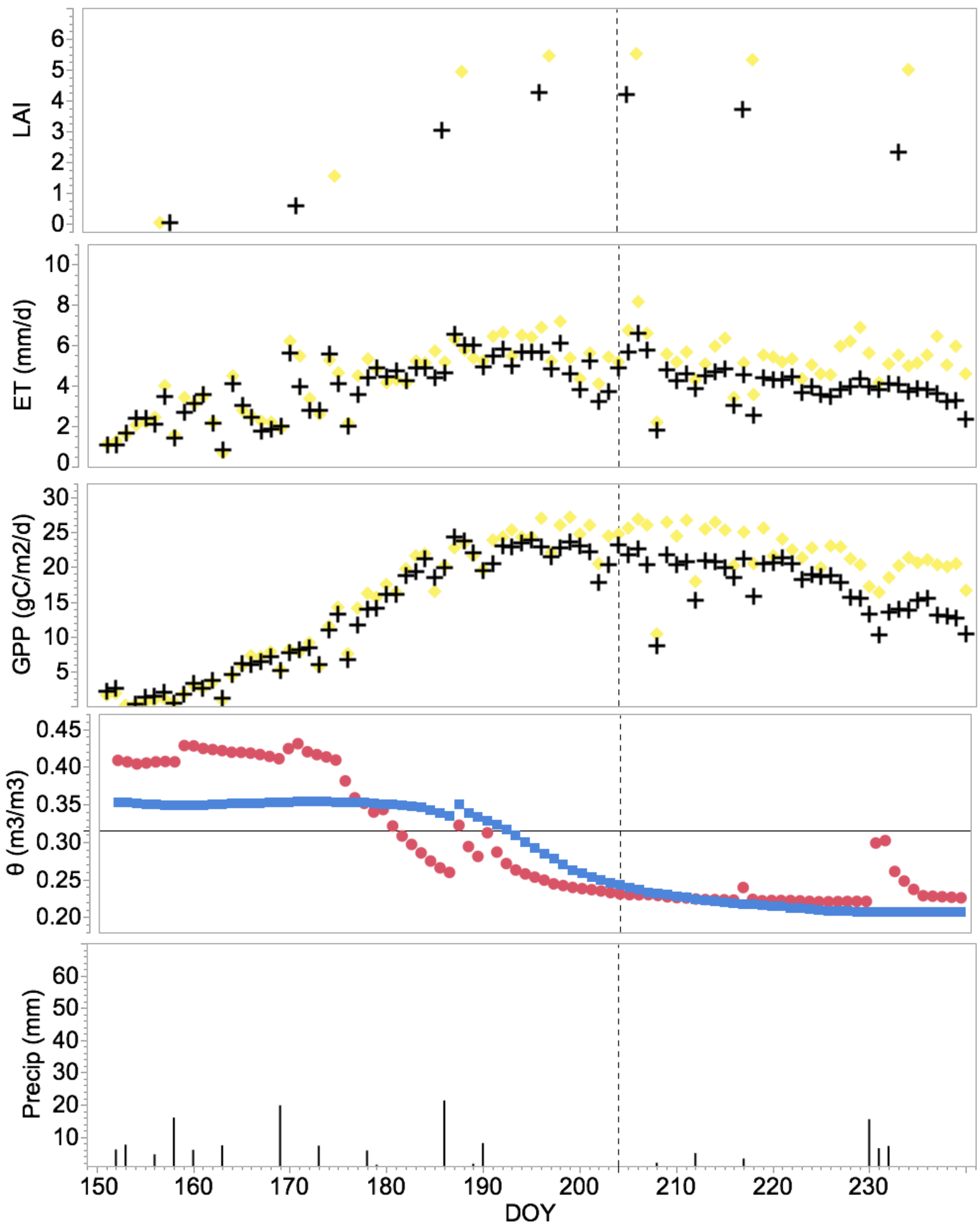

Figure 1. Daily biophysical data (from top to bottom): Leaf Area Index (LAI), Evapotranspiration (ET), Gross Primary Productivity (GPP) at IMS (yellow diamond) and RMS (black crosses); Volumetric Water Content (θ) at RMS 10 cm

(red circles) and 50 cm (blue squares), and precipitation (mm) from DOY 151-240 in the 2003 season. The silking date is denoted by the dotted vertical line and the solid horizontal line represents a fraction of available soil water of 0.5 at the 10 cm and 50 cm depths.

Another way to demonstrate the effect of the flash drought in 2003 is with the latent heat ratio. The latent heat ratio (LE ratio) is given in Equation 3 as the ratio of available energy (i.e., Rn-G) partitioned to latent heat between RMS and IMS. An LE ratio greater than 1.0 reflects that proportionally more available energy at RMS was partitioned to LE than at IMS. Conversely, an LE ratio less than 1.0

$$\text{LE ratio} = [\ \text{LE}_{\text{RMS}} / (\text{Rn-G})_{\text{RMS}}] / [\ \text{LE}_{\text{IMS}} / (\text{Rn-G})_{\text{IMS}}] \qquad (3)$$

When soils were sufficiently moist in the early part of the 2003 C90, the 10-day averaged LE ratio in the was greater than 1.0 over the hours sampled except for the 1600L hour (Fig. 2). This would imply that water stress was either minimal or non-existent at RMS and thus, stomatal conductance was not adversely affected. Unfortunately for the maize at RMS, the moist soils did not last past the first month of the C90 as the flash drought set in.

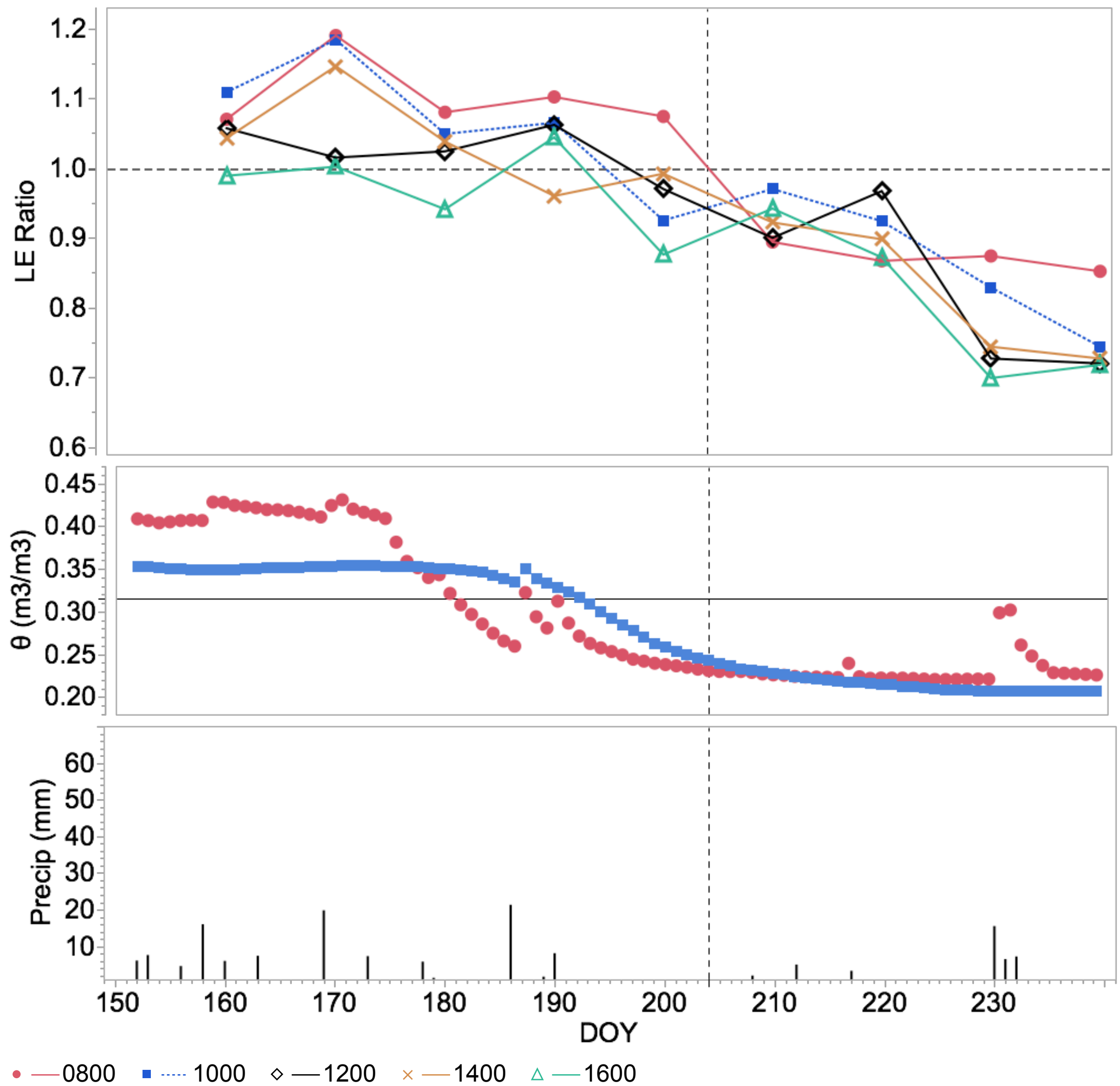

Figure 2. From top to bottom: Median ratio of available energy (i.e., Rn-G) partitioned to latent heat (LE) between the rainfed maize field (RMS) and the irrigated maize field (IMS) over 10-day periods from day of year (DOY) 151-160 in the 2003 season, volumetric Water Content (θ) at RMS 10 cm (red circles) and 50 cm (blue squares), and precipitation (mm) from DOY 151-240 in the 2003 season. The silking date is denoted by the dotted vertical line and the solid

horizontal line represents a fraction of available soil water of 0.5 at the 10 cm and 50 cm depths.

As the season progressed and soil water became more depleted, the LE ratios started decreasing and were less than 1.0 for all hours of the day by the time maize entered into the reproductive stage. The biggest change occurred between the 10-day period ending DOY 190 and the 10-day period ending DOY 210. In the former, the LE ratio was still greater than 1.0 for all hours except 1400L. In the latter, the LE ratio was less than 1.0 over all hours, and was safely below 1.0 in the early part of the afternoon.

A quick peak at soil water in Figure 2 explains why this would be the case. In the 10-days leading up to DOY 190, there was some precipitation which temporarily brought the soil water content at 10 cm above $\theta_{50\%}$ and kept the soil water at 50 cm safely above $\theta_{50\%}$. However, that precipitation event was the last one over 10 mm for over forty days and soil water declined below $\theta_{50\%}$ at both 10 cm and 50 cm shortly after DOY 190 and remained there for the duration of the season.

The prolonged period with soil water stress had increasingly adverse effects on stomatal conductance. By the end of the season, the 10-day average LE ratio was significantly below 1.0 for all hours sampled and even dipped below 0.7 at the 1600L hour over the 10-day period ending DOY 230. The precipitation that fell early in the final 10-day period of the C90 did slightly moisten the soils. However, the moisture was too little and possibly too late to be of help at alleviating the stress in the maize crop and the LE ratio did not improve.

The C90 in 2005 began in much the same way as the C90 in 2003: regular precipitation that kept soils at RMS reasonably moist, which led to comparable daily rates of ET and daily accumulation of GPP to those at IMS. Also, as in 2003, a prolonged dry spell began during the vegetative stage and precipitation events for the remainder of the season were sparse. Differences in accumulations of ET and GPP between RMS and IMS during the C90 in 2005 were also comparable to 2003, with IMS outpacing RMS in total ET by 49 mm (64 mm in 2003) and by 185 g C/m^2 (210 g C/m^2 in 2003). The 2005 season was actually the driest season in the study period and had the lowest frequency of precipitation. Thus, the two dry seasons had much in common.

There was a key difference between the two seasons, however. As discussed earlier and shown in Table 2, only 10 mm of precipitation fell during the most critical 31-day window in the 2003 GS. Conversely, a total of 108 mm fell during the 31-day window in 2005, with most of it coming with one storm on DOY 206. The main dry spell in the 2005 C90 occurred between DOY 165 and DOY 195. Precipitation in this period was almost non-existent and the dry spell led to a decline in soil water below $\theta_{50\%}$ at both 10 cm and 50 cm by the onset of silking. Much as in the 2003 flash drought, daily ET rates and daily accumulations of GPP at RMS became reduced compared to those at IMS during the dry spell (Fig. 3). The 10-day average LE ratio for the period ending DOY 190 was less than 1.0 for all hours and significantly less than 1.0 during the afternoon hours as a result of the soil water stress (Fig. 4)

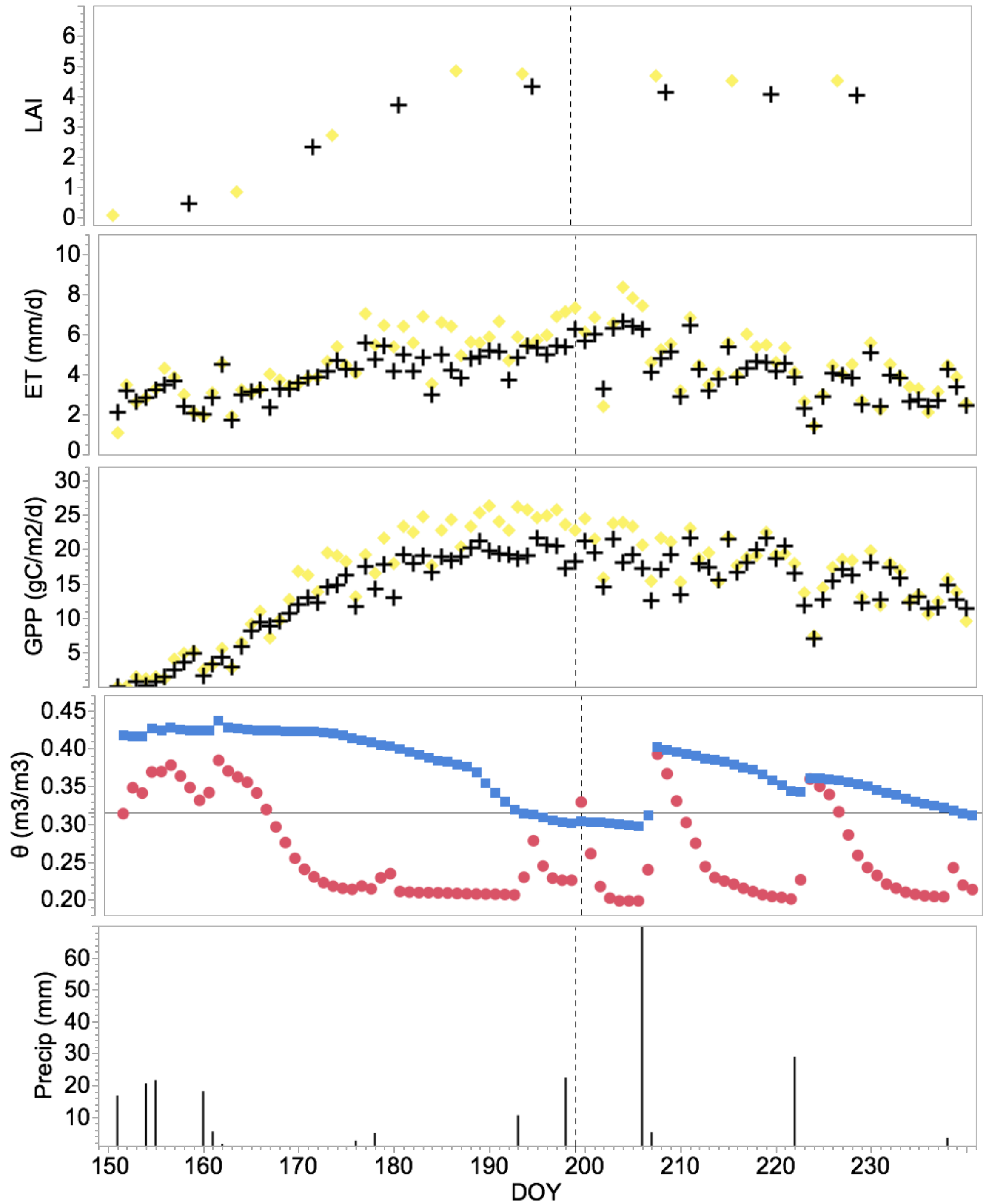

Figure 3. Daily biophysical data (from top to bottom): Leaf Area Index (LAI), Evapotranspiration (ET), Gross Primary Productivity (GPP) at IMS (yellow diamond) and RMS (black crosses); Volumetric Water Content (θ) at RMS 10 cm (red circles) and 50 cm (blue squares), and precipitation (mm) from DOY 151-240

in the 2005 season. The silking date is denoted by the dotted vertical line and the solid horizontal line represents a fraction of available soil water of 0.5 at the 10 cm and 50 cm depths.

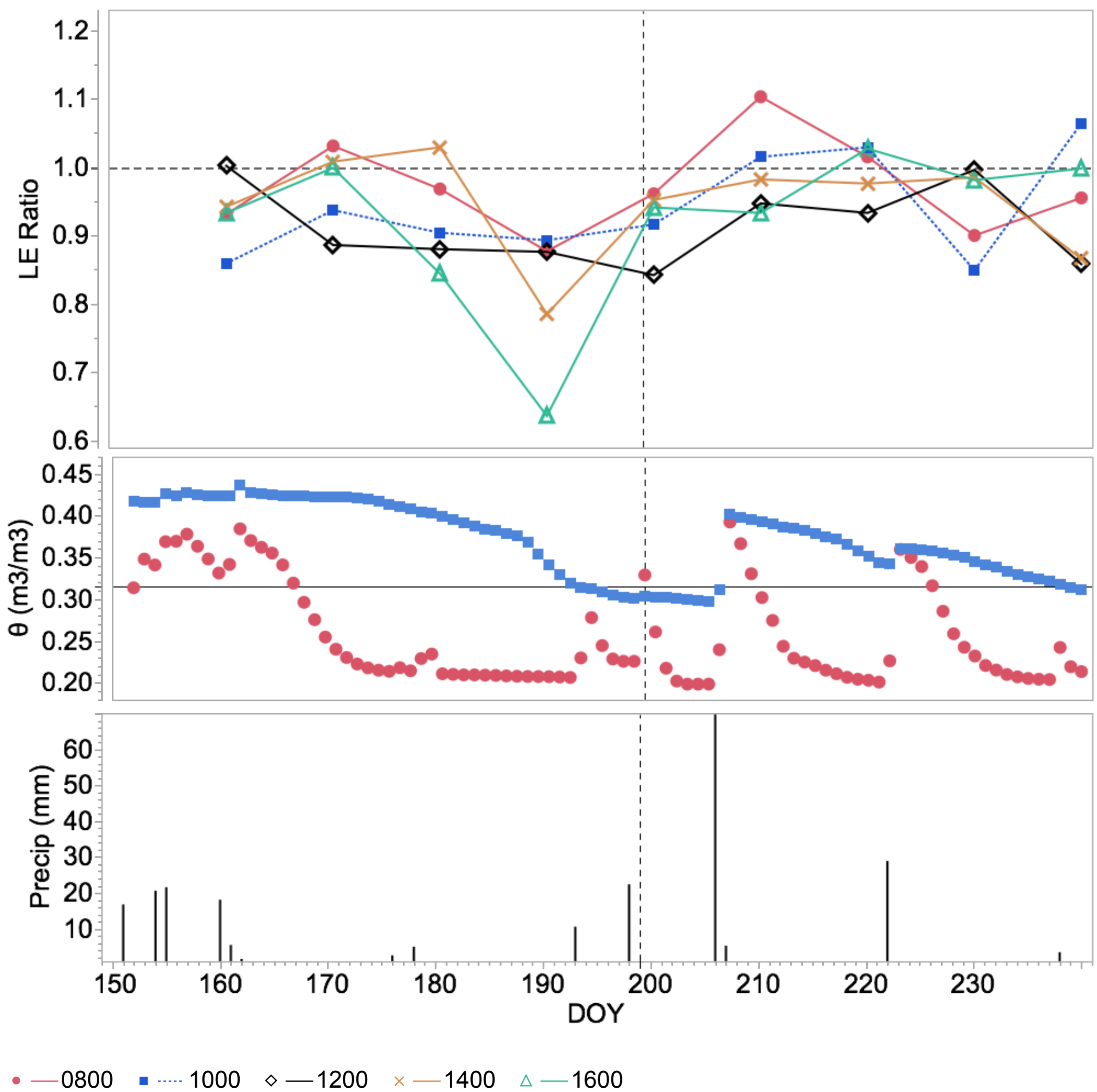

Figure 4. From top to bottom: Median ratio of available energy (i.e., Rn-G) partitioned to latent heat (LE) between the rainfed maize field (RMS) and the irrigated maize field (IMS) over 10-day periods from day of year (DOY) 151-160

in the 2005 season, volumetric Water Content (θ) at RMS 10 cm (red circles) and 50 cm (blue squares), and precipitation (mm) from DOY 151-240. The silking date is denoted by the dotted vertical line and the solid horizontal line represents a fraction of available soil water of 0.5 at the 10 cm and 50 cm depths.

A week after the onset of silking in the 2005 GS (DOY 206), the situation looked fairly dire for the maize crop at RMS. It was the fourth consecutive day of maximum temperatures over 37°C, the soil water content at both 10 cm and 50 cm were safely below $\theta_{50\%}$, and the gap in daily ET rates and in daily GPP accumulations were growing more significant. The LAI at RMS had not begun to decrease markedly compared to IMS as was the case in the 2003 flash drought, but it was likely if precipitation did not materialize soon. However, that evening a major thunderstorm rolled through the region, bringing over 70 mm of precipitation and much cooler weather.

This notable rainfall event was beneficial to the maize crop at RMS. Figure 3 shows that the increase in soil water from the event led to more equivocal daily rates of ET and much closer rates of daily GPP accumulation between IMS and RMS in the days after the storm. Perhaps the clearest example of stress alleviation with the storm though is in the LE ratio. Figure 4 shows that the 10-day averaged LE ratio ending on DOY 210 was greater than 1.0 in the morning hours and was not significantly below 1.0 during the afternoon hours. Thus, the recharged soil profile brought an almost immediate response in the form of increased stomatal conductance at RMS compared to a few weeks earlier when it was much drier.

There were only two more precipitation events the remainder of the C90 in 2005. One of them on DOY 222 was significant enough to re-moisten the soil profile, particularly at 10 cm, which had dried out again. This kept the daily rates of ET and accumulation of GPP somewhat close to that of IMS for most of the remainder of the season.

As the C90 in 2005 came to a close, another dry spell was underway and as mentioned earlier, 2005 would end up being the driest growing season in the study period. However, the difference between 2003 and 2005 was one major storm during the critical period. In the critical 31-day period in 2003, precipitation was almost non-existent, and the maize crop gradually deteriorated as water stress caused stomata to “close” at progressively earlier time in the day. In the critical 31-day period in 2005, a significant precipitation event recharged the soil profile and allowed stomatal conductance to recover to levels from earlier in the season. Without that storm, it would be fair to assume that the maize yields in 2005 season would have been worse than in 2003 as all indications from the biophysical parameters were worse entering the critical period in 2005 than in 2003.

3.2 Wet seasons

As discussed in chapter 2, the later seasons of the study period were wetter than the 30-year average, especially the 2007 and 2008 seasons. During the C90 analyzed for this chapter, a total of 379 and 367 mm of precipitation fell in 2007 and 2009 respectively. However, as with the dry season comparison in the previous subsection, this wet season comparison will show that the seasons were not equivalent in terms of the timing or frequency in precipitation.

As discussed in chapter 2, the 2007 growing season started very wet and thus soil water was plentiful by the beginning of the C90. However, after some modest precipitation events in the first few weeks of the C90, a dry spell began and soil water decreased. The period of the dry spell (DOY 165-190) was remarkably similar to the 2005 season and the effects were similar. Soil water went below $\theta_{50\%}$ at 10 cm within days and the decline began at 50 cm about a week later. As soil water stress became more prevalent, gaps in the daily ET rates and daily GPP accumulations began to grow between IMS and RMS. The gaps were largest right before silking, particularly with GPP as IMS daily accumulations were ~ 25 g C/m^2 and RMS daily accumulations were generally around 20 g C/m^2 in that period (Fig. 5).

The LE ratio (Fig. 6) was also affected by the dry spell and the pattern was similar to that in 2005 in that there was a large drop off between DOY 180 and DOY 190. The difference is that in 2007 the morning hours seemed to be affected by the dry spell as much as the afternoon hours, whereas in 2005 the stress was considerably worse in the afternoon. The other similarity is that there was a decent precipitation event immediately preceding silking that boosted soil water at RMS. However, this is where the similarities between 2005 and 2007 start to diverge.

The 2005 season was the driest in the study period but it had the most precipitation in the crticial period (108 mm) of any season with maize as the common crop. The 2007 season was the second wettest in the study period but only

67 mm of the season total came in the 31-day critical period around silking. While this was certainly was better than the flash drought of 2003, no individual precipitation event was enough to alleviate the stress at 10 cm. As the critical period progressed, soil water at 50 cm also fell below $\theta_{50\%}$ and the signs of mild water stress prevailed. Daily accumulation of GPP and daily ET rates remained less at RMS than at IMS, though not as significant of a difference as in the 2003 flash drought case.

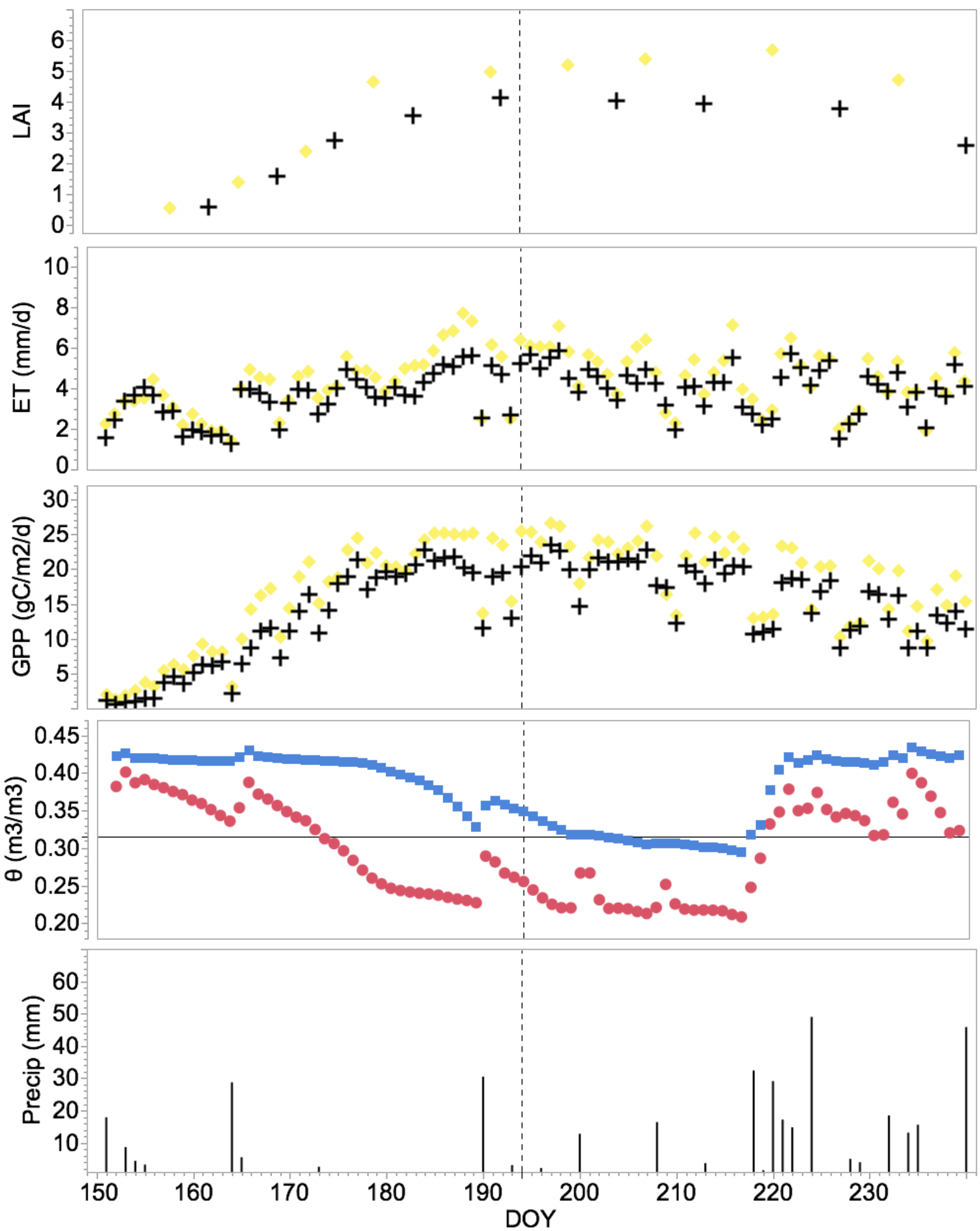

Figure 5. Daily biophysical data (from top to bottom): Leaf Area Index (LAI), Evapotranspiration (ET), Gross Primary Productivity (GPP) at IMS (yellow diamond) and RMS (black crosses); Volumetric Water Content (θ) at RMS 10 cm (red circles) and 50 cm (blue squares), and precipitation (mm) from DOY 151-240

in the 2007 season. The silking date is denoted by the dotted vertical line and the solid horizontal line represents a fraction of available soil water of 0.5 at the 10 cm and 50 cm depths.

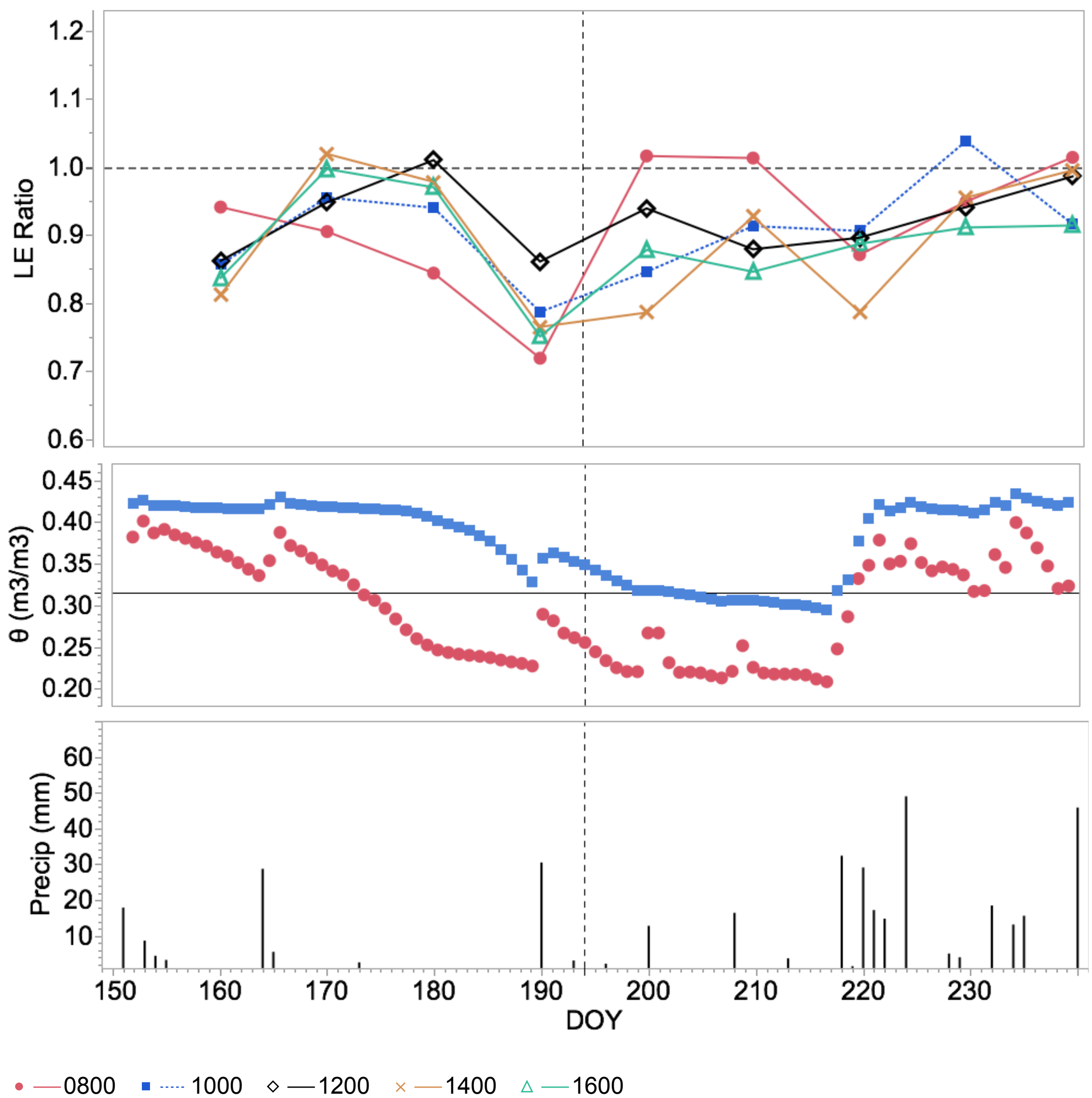

Figure 6. From top to bottom: Median ratio of available energy (i.e., Rn-G) partitioned to latent heat (LE) between the rainfed maize field (RMS) and the irrigated maize field (IMS) over 10-day periods from day of year (DOY) 151-160

in the 2007 season, volumetric Water Content (θ) at RMS 10 cm (red circles) and 50 cm (blue squares), and precipitation (mm) from DOY 151-240. The silking date is denoted by the dotted vertical line and the solid horizontal line represents a fraction of available soil water of 0.5 at the 10 cm and 50 cm depths.

While the 2005 season had the major precipitation event during the critical period, which more or less "saved" the maize crop at RMS, the 2007 season had some modest precipitation events in July that prevented significant water stress and therefore kept the crop going. After the 31-day critical period was over, significant precipitation returned to the region and soils were generally very moist for the remainder of the season. During the moist finish to the season, the 10-day averaged LE ratios were closer to 1.0, especially in the morning. However, the gap in daily ET rates and daily GPP accumulations did not change much over the later period where soils at RMS were moist. A closer look at the LAI in Figure 5 shows why this gap remained.

The LAI of maize generally increases rapidly in the first few months after planting (i.e., early and middle vegetative stage) and reaches a maximum around silking. Thus the maximum LAI is highly susceptible to water stress in this period. In the 2007 season, the dry spell coincided with the period when LAI was starting to reach its peak and thus, the max LAI at RMS was limited to a maximum of 4.1 from measurements taken on DOY 192. Conversely at IMS, where water-stress was avoided, LAI peaked at 5.7 about three weeks after the onset of silking. This higher LAI therefore permitted greater rates of ET and accumulations of GPP at

IMS than at RMS, even when soils were moist at RMS in the later portion of the 2007 season.

Precipitation was also above the 30-year median in the 2009 season, though was considerably less than the 2007 season. During the C90 in 2009, precipitation totaled 367 mm, 12 mm less than in 2007. However, the timing of precipitation was much more equitable in 2009 than in 2007 and there were no prolonged periods of water stress. Figure 7 shows that the early portion of C90 had frequent precipitation and soils remained moist at both 10 cm and 50 cm. The moist soils at RMS allowed the LAI to increase at a similar rate as at IMS for the first month of the C90. ET rates and daily accumulations of GPP were also very comparable during this period.

There was a bit of water stress at 10 cm between DOY 180 and silking (DOY 197), which did cause a flattening of the LAI at RMS compared to IMS and a significant decrease in the LE ratio in the afternoon hours. However, this drier spell coincided with a period that was considerably cooler than average, and thus water stress was lower than it could have been in a season that was much warmer. Still, the LAI at RMS flattened out during this period, while it continued to increase at IMS. Interestingly enough the short period of water stress did not have a major effect on the daily ET rates at RMS as they were nearly identical as those at IMS, even though the LAI at IMS was higher. However, it’s possible the cooler than normal temperatures during the period allowed for ET rates to remain very comparable between IMS and RMS. Daily accumulations of GPP were slightly less at RMS but not significantly so.

The brief period of water stress at RMS ended on the silking date when 36 mm of precipitation fell and moistened soils again. The response from the maize crop was immediate, as evidenced by the LE ratio in Figure 8. In the 10-day averaged LE ratio ending on DOY 200 in 2009, all hours of the day had an LE ratio above 1.0, indicating that the minor water stress at RMS had been alleviated.

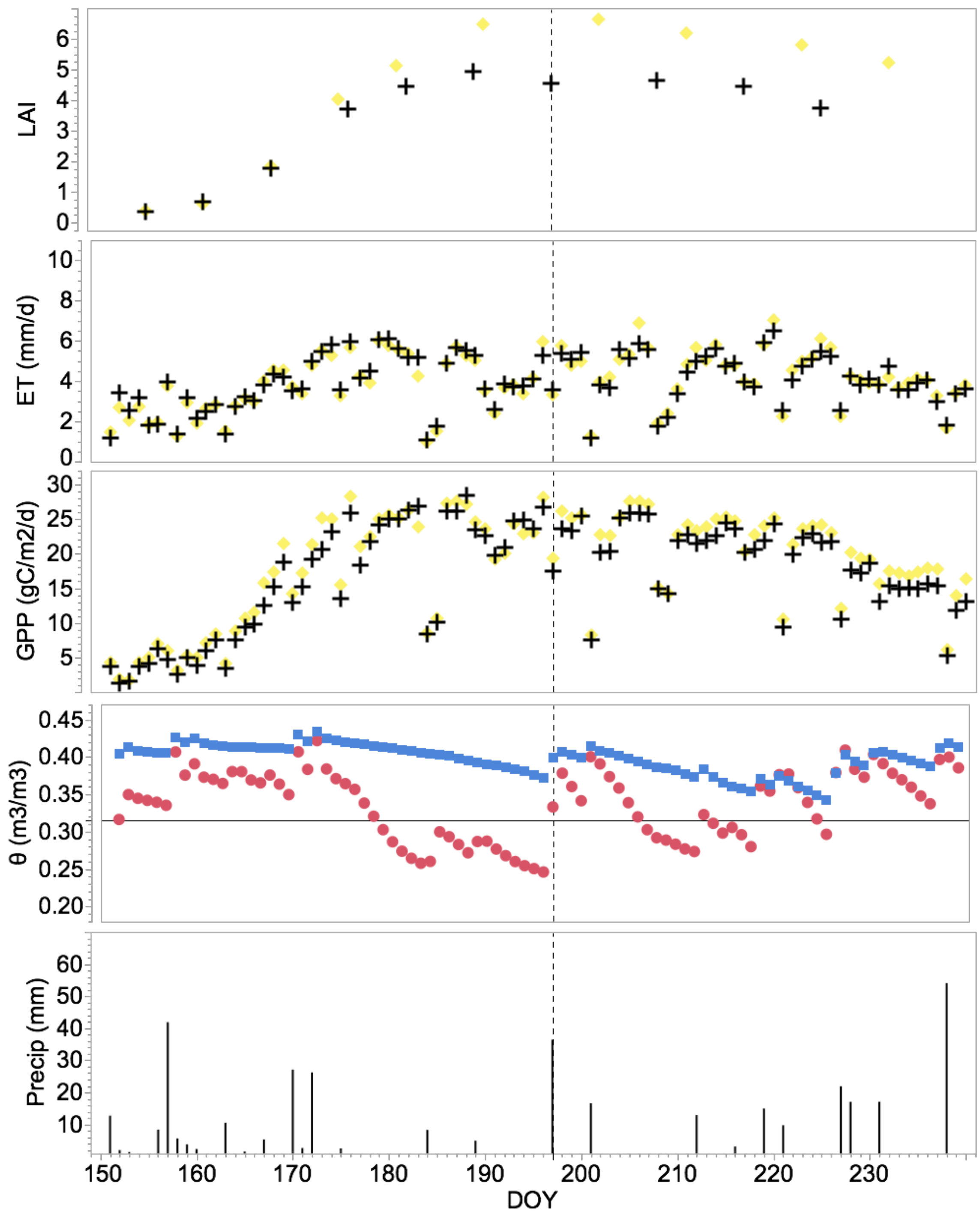

Figure 7. Daily biophysical data (from top to bottom): Leaf Area Index (LAI), Evapotranspiration (ET), Gross Primary Productivity (GPP) at IMS (yellow diamond) and RMS (black crosses); Volumetric Water Content (θ) at RMS 10 cm (red circles) and 50 cm (blue squares), and precipitation (mm) from DOY 151-240 in the 2009 season. The

silking date is denoted by the dotted vertical line and the solid horizontal line represents a fraction of available soil water of 0.5 at the 10 cm and 50 cm depths.

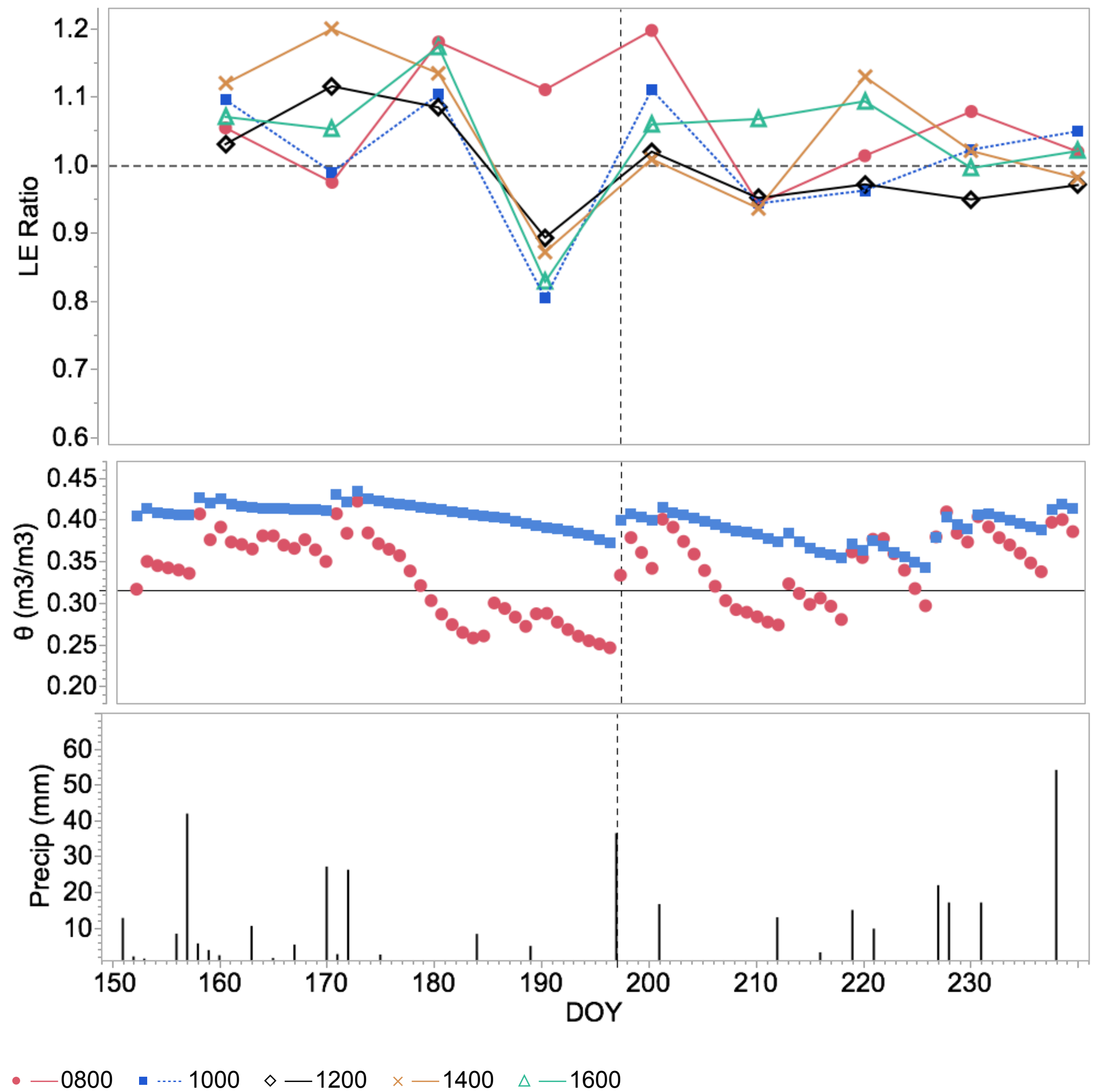

Figure 8. From top to bottom: Median ratio of available energy (i.e., Rn-G) partitioned to latent heat (LE) between the rainfed maize field (RMS) and the irrigated maize field (IMS) over 10-day periods from day of year (DOY) 151-160 in the 2009 season, volumetric Water Content (θ) at RMS 10 cm (red circles) and

50 cm (blue squares), and precipitation (mm) from DOY 151-240. The silking date is denoted by the dotted vertical line and the solid horizontal line represents a fraction of available soil water of 0.5 at the 10 cm and 50 cm depths.

The remainder of the 2009 season featured several modest precipitation events and continued cooler than average temperatures, and there were no prolonged periods of soil water stress. Thus, daily ET rates at RMS remained almost identical to those of IMS throughout the remainder of the C90. Daily accumulations of GPP were a bit less at RMS than at IMS, which as in 2007, could be explained by the lower LAI at RMS. Still, the accumulated GPP at RMS during the C90 was only 112 g C/m^2 less than at IMS and at 1543 g C/m^2, it was by far the highest accumulation of GPP of any season when maize was the common crop at RMS and IMS.

4.0 Summary and Conclusions

Dry periods were common in the study period. Every season, except the 2009 GS, had at least one 10-day period with less than 10 mm of precipitation at RMS. However, as shown in chapter 2, timing of precipitation was very important. For example, the 2005 GS actually had more 10-day periods (5 total) with less than 10 mm of precipitation than the 2003 flash drought season (3 total). However, the overall maize yields were higher in 2005 (see Table 1) due to the occurrence of a couple of significant precipitation events in what was otherwise a very dry season. Likewise, maize yields were much higher in 2009 than in 2007, even though the

2007 GS had more precipitation. The difference again was timing. In the 2007 GS, a significant portion of the precipitation fell in mid-to-late August, but was somewhat dry during the critical period from just before to a few weeks after silking. Conversely, in the 2009 GS, regular precipitation occurrences prevented prolonged water stress, especially during the aforementioned critical period.

As expected, total ET and GPP were higher, sometimes significantly so, at IMS than at RMS over this period. ETp was very consistent within a season between RMS and IMS and with the exception of the abnormally cool 2009 season, was fairly consistent between seasons. During the dry spells, soil water stress often caused noticeable reductions in the LE ratio, as the closing of stomata in response to a lack of soil water led to less of the available energy being portioned to latent heat at RMS compared to IMS. During the inception of water stress, this effect was strongest in the afternoon hours. As the water stress persisted, the effect was realized earlier in the day.

Maize at RMS did appear to have some resilience, and while we can only imply levels of stomatal conductance from the figures shown, it seems clear from the ET and GPP data and the LE ratios that a significant recharge of soil water after incipient water stress can lead to rejuvenation of the maize crop, even if the potential yield has been cut. The biggest difference between 2005 and 2003 was a major storm occurred at a point of stress in 2005 and not in 2003. If a storm of equal magnitude had occurred during the critical period in 2003, it is very likely that we would only be discussing 2003 as a bit drier than normal season with a modest reduction in overall yield potential and not as an idealized flash drought scenario.

5.0 Acknowledgements:

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CHAPTER 4: MONITORING THE EFFECTS OF RAPID ONSET OF DROUGHT ON NON-IRRIGATED MAIZE WITH AGRONOMIC DATA AND CLIMATE-BASED DROUGHT INDICES

Abstract

The 2003 growing season at Mead, NE began with moist and relatively cool conditions that persisted through most of June. During this moist phase of the season, soil water and parameters such as evapotranspiration (ET) and gross primary productivity (GPP) were nearly identical between a rainfed maize site (RMS) and an irrigated maize site (IMS). A drying phase began in late June, causing decline in soil water at RMS and the necessity of irrigation treatments at IMS. The drying phase turned into a "stressed" phase by early August, as only 10 mm of precipitation fell in a forty day period between mid-July and late August. Conditions at RMS began to deteriorate even more rapidly after maize entered the critical reproductive stage, as the depletion of soil water led to (implied) reductions in stomatal conductance, which led to significant reductions in ET and GPP, compared to the well-watered IMS. Two drought indices, the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI), were utilized to show the effectiveness of short-term indices at detecting flash drought versus field measurements. Results showed that both the 1-month SPI and the 1-month SPEI were quite sensitive to the onset of the flash drought and closely followed the decline in soil water and other biophysical parameters at RMS relative to IMS. Significant precipitation returned and led to some recharge prior to harvest but was far too late to be of any help to the maize at RMS, as the yield difference of 6.3 Mg/ha between RMS and IMS revealed the

detrimental effects of a rapid onset of drought during the critical reproductive stage of maize.

1.0 Introduction

Soil water is an integral part of the hydrologic cycle and a critical parameter for plant growth and development. Dale and Shaw (1965) reported that soil water is one of the most critical factors for crop development and yield. Soil water stress at the silking stage of maize (*Zea mays* L.) can reduce grain yield by 50% (Denmead and Shaw, 1960) and an omission of a single irrigation treatment at a critical stage could reduce maize yields by up to 40% (Cakir, 2004). Meyer et al. (1993) reported that maize was most sensitive to water stress in the silking-blister dough stage and Calvino et al. (2003) showed a curvilinear response of maize yield to available water in the three weeks preceding and following silking. Earl and Davis (2003) reported maize yield reductions up to 85% during severe water stress that occurred after the sixth leaf stage in Georgia. Thus, it is well established that a lack of soil water causes stress and yield reduction in maize. But soil water is not a commonly measured variable at NOAA Cooperative (COOP) weather stations and there are but a handful of networks around the United States where soil water is a standard, quality controlled observation (Hollinger and Isard, 1994; Illston et al. 2008; Hubbard et al. 2009).

Drought is a natural, recurring phenomena that occurs everywhere at various points in time and is occurring somewhere on Earth at any given point of time. Drought is a complex topic with ecosystem impacts that vary with its intensity and duration and socio-economic impacts that often magnify problems for the most vulnerable members of society. Perhaps it is fitting that drought does not have a universal definition and is often considered in the context of four broad categories defined by Wilhite and Glantz (1985): meteorological, agricultural, hydrological, and socioeconomic.

Short-term drought, sometimes referred to as flash drought, is a rapid onset of drought often accompanied by high temperatures and winds that lead to rapid soil moisture depletion during a critical time in the growing season (Svoboda et al. 2002). Flash droughts can occur within a longer period of normal or above normal precipitation and bring devastating agricultural impacts. For example, although precipitation was above normal in most of Oklahoma during 1998, an intense, short-term drought during the summer decimated the state's cotton and peanut crop (Basara et al. 1998; Illston and Basara, 2003). Illston et al. (2004) described four phases of soil moisture in a flash drought case in Oklahoma: a moist plateau in the spring, transitional drying early in the summer, enhanced drying mid-summer into early autumn, and recharge during the cooler months of late autumn and winter.

The 2003 growing season at Mead, NE closely matches the description of flash drought given in Svoboda et al. (2002). It began with moist and cool conditions that persisted through much of June. However, a prolonged period of minimal precipitation with periodic spells of heat led to a rapid decline in soil water at a rainfed maize site compared to a nearby irrigated site, which led to significant reductions in biophysical parameters such as evapotranspiration (ET) and gross primary productivity (GPP). The time series of soil moisture from the growing season at the rainfed maize site closely follows the four phases introduced in Illston et al. (2004). Thus, the primary goal of this paper is to show the relationship between soil water and agroecological parameters (ET and GPP) during four phases of the growing season. A secondary goal of this paper is to show the utility of using short-term and longer-term drought indices for monitoring a flash drought that occurred during the critical reproductive stage of maize at a rainfed site. The remainder of this section describes a short history of drought indices, with a particular focus on the two normalized drought indices used in this study- the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evaporatranspiration Index (SPEI).

Palmer (1965) developed the Palmer Drought Severity Index (PDSI) with an objective of “developing a general methodology for evaluating drought in terms of an index that permits time and space comparisons of drought severity." The PDSI is calculated from a simple water balance model that uses factors such as precipitation, temperature and latitude for the calculation of potential evapotranspiration (Thornthwaite, 1948), recharge, runoff, and soil moisture loss to determine whether recent precipitation was sufficient to maintain a normal water balance. The PDSI is divided into 11 categories ranging from extreme drought to extreme wet spell (Heim, 2002).

McKee et al. (1993) developed the Standardized Precipitation Index (SPI) in response to demand from Colorado decision makers for an index that expressed current conditions in terms of water supply, deficit, and probability. The SPI has the advantage of being spatially invariant and an indicator of drought on multiple time scales (Guttman, 1999), though caution has been advised when comparing the SPI between sites with very different periods of record and at short time scales during distinct dry seasons (Wu et al. 2005).

The SPI has been widely used for operational and research purposes. Hayes et al. (1999) showed that the SPI detected drought conditions a full month ahead of the PDSI during the U.S. southern Plains drought of 1996. Livida and Assemakopoulos (2007) used the SPI to show that mild and moderate drought were more common on the three- and six- month time scale across northern Greece while severe drought was more frequent across southern Greece. Brown et al. (2008) integrated the SPI with satellite derived vegetation metrics and biophysical data to produce 1-km maps of the Vegetation Drought Response Index (VegDRI). McRoberts and Nielsen-Gammon (2012) used daily precipitation from the Advanced Hydrologic Prediction Service multisensor precipitation estimates (MPE) and COOP station data to obtain a high resolution SPI to be used as guidance for the U.S. Drought Monitor (Svoboda et al. 2002). Thus, it was recommended by the World Meteorological Organization to be the primary drought index for national meteorological and hydrological agencies in monitoring meteorological drought across the globe (Hayes et al. 2011).

One criticism of a precipitation-only index like the SPI is that it does not account for temperature effects on drought. For example, Hu and Wilson (2000) showed that the temperature and precipitation dependent PDSI was affected by both large anomalies of temperature and precipitation in the central United States. Vicente-Serrano et al. (2010) addressed this issue with the development of the

SPEI. The SPEI is based on the monthly (or weekly) difference between precipitation and potential evapotranspiration (ET_p), using the ET_p method from Thornthwaite (1948). The Thornthwaite method of ET_p was chosen over more robust methods, such as the Penman-Monteith (Monteith, 1964), due to the simplicity of its calculation and its reasonable performance when calculating a drought index, such as the PDSI (Mavromatis, 2007).

The development of drought indices allows for useful comparisons of conditions between locations and over long periods of time. However, caution should still be applied when applying an index to long time-series of climate data. Inhomogeneities in data from station relocations, instrumentation changes, and growth of vegetation and urban boundaries do exist and analyses can be erroneous if these items are not accounted for (Peterson et al. 1998). Nevertheless, climate-based drought indices are useful at identifying the severity and duration of drought and continued research will only make existing indices more accurate and robust.

2.0 Materials and methods

2.1. Study site

The CSP is located at the University of Nebraska-Lincoln (UNL) Agricultural Research and Development Center near the town of Mead, NE. The CSP commenced in the spring of 2001 and consists of three sites. The first agroecosystem is an irrigated, continuous maize (ICM) site centered at 41˚09’54.2” N, 96˚ 28’35.9” W with an irrigated area of 48.7 ha. The second agroecosystem is an irrigated, rotated maize-soybean (IMS) site centered at 41˚09'53.5" N, 96˚ 28'12.3" W with an irrigated area of 52.4 ha. Both ICM and IMS were irrigated rotations of maize and soybeans under no-till in the ten years prior to the initialization of the CSP. The third agroecosystem is a rainfed, rotated maize-soybean (RMS) site centered at 41˚10'46.8" N, 96˚ 26'22.7" W with an area of 65.4 ha. Prior to the CSP, RMS had 2-4 ha plots of maize, soybeans, wheat, and oats with tillage (Verma et al. 2005). ICM was not considered in this analysis as its management practice (i.e., continuous maize) made it less comparable to RMS than IMS.

Each CSP site consists of six, 20 m x 20 m intensive management zones, hereafter referred to as IMZ's, where detailed process-level studies of soil water, soil carbon dynamics, canopy and soil gas exchange, crop growth and biomass partitioning are established. Prior to the onset of the CSP in 2001, all three sites were uniformly tilled by disking the top 10 cm to incorporate Phosphorous (P) and Potassium (K) fertilizers and to homogenize the soil layer (Suyker and Verma, 2009). Nitrogen (N) fertilizer applications were applied to IMS and RMS prior to planting in 2003; subsequent N applications were applied in June at IMS through the center-pivot system in a process known as fertigation.

The IMZ locations were selected using k-means clustering applied to six layers of 4 m x 4 m cells based broadly on soil type, topography, and crop production potential within each site. Fine-scale spatial information used for each site included a digital soil map, a digital elevation model, a Veris map of soil electrical conductivity (0-30 cm), near infrared reflectance of bare soil from the

IKONOS satellite (4 km resolution), and a map of soil organic matter (0-20 cm). Interpolation onto a 4 x 4 m grid was done by kriging.

2.2 Eddy covariance flux method and measurement

Toward the middle of each field is an eddy covariance tower installed for measurements of CO_2 and H_2O fluxes. The eddy covariance method is used to measure the exchange of CO_2 and H_2O between the biosphere and atmosphere at over a hundred sites worldwide and has produced defensible estimates of carbon exchange. The method works by sampling atmospheric turbulence to determine the net difference of material going across the atmosphere-canopy interface (Baldocchi et al. 1988; Baldocchi, 2003).

CO_2 fluxes were measured with an array of sensors- a three-dimensional sonic anemometer (R3, Gill Instruments Ltd., Lymington, UK) and a closed-path CO_2/H_2O system (LI 6262, Li-Cor Inc., Lincoln, NE) . H_2O fluxes were measured with an open-path CO_2/H_2O sensor (LI 7500, Li-Cor Inc., Lincoln, NE). Further details are given in Verma et al. 2005 and Suyker et al. 2003. Eddy covariance sensors were mounted at a height of 3.0 m above the ground until canopy height exceeded 1.0 m. When canopy height exceeded 1.0 m, the eddy covariance sensors were moved to a height of 6.0 m, a height they remained at until harvest.

The CO_2 storage in the layer below the eddy covariance sensors was calculated from CO_2 concentration profile measurements and added to the measured CO_2 flux to obtain the net ecosystem exchange (NEE). Estimates of daytime ecosystem respiration were obtained from the night-NEE relationship, which is explained further in Xu and Baldocchi, 2004. The gross primary productivity (GPP) was obtained by taking the difference of NEE and ecosystem respiration. All GPP values in this paper represent a daily average in units of g $C/m^2/d$.

2.3 Soil moisture sensors

Dynamax Theta probes were installed in the spring of 2001 at depths of 10, 25, 50, and 100 cm as part of three IMZ's in IMS and four in RMS. Soil moisture sensors at 10 and 25 cm were removed from all IMZ's during planting and harvest periods and then reinstalled in the same location.

The soil moisture probes were installed at a 45° angle from vertical to the surface at 10 and 25 cm and were installed using the drip loop method at 50 and 100 cm. Theta probes contain a waterproof enclosure, sensing head, and a cable. The enclosure has a measurement circuitry and an oscillator, while the sensor head consists of three outer rods that surround an inner rod. The rods act as a transmission line and develop an impedance that is dependent on the dielectric constant of the soil. Topp et al. (1980) showed that a linear relationship exists between the volumetric water content and the dielectric constant. Thus, soil volumetric water content (θ) is the standard soil water variable in the CSP, as in the Nebraska AWDN (Hubbard et al. 2009; You et al. 2010).

Soil water data from the CSP underwent significant quality control before its release. Data that were classified as questionable were replaced by previous day's values if only one day was bad and by linear interpolation if more than one day was bad. Meteorological data from the IMZ's were examined for incidence of precipitation prior to use of interpolation. Automated soil moisture measurements were collected hourly and averaged daily over the span of the project.

2.4 Soil water calculations

Each field only has one eddy covariance tower and thus, only one set of measurements of ET, GPP, and related parameters; the nature of these measurements leads to their representation of a footprint. It is therefore necessary to scale up soil water measurements from point values to aerial values before comparisons can be made with ET. The footprints of the IMZ's are not equal in area and thus field-averaged calculations of soil water are weighted by Equation 1 below, where w_i is the weight (i.e., fraction of the field represented by the fuzzy classes associated with the i'th IMZ), x is the measured soil water in the i'th IMZ and i increases from 1 to n (the total number of IMZs per field). Weights were assigned to each IMZ based on the proportional area of the fuzzy class represented.

$$\bar{x} = \sum_{i=1}^{n} w_i x_i \tag{1}$$

Prior to the study, soil samples were collected from all IMZ's at the three sites and were analyzed in the laboratory for soil type and water holding capacity. Silt clay loam is the predominant soil texture at IMZ's in both fields. Field capacity and wilting point values at the three sites were determined by averaging the -1/3 bar values and the -15 bar values respectively from moisture release curves determined in the laboratory. A fraction of available soil water (F_{AW}) was calculated via Equation 2 for a direct comparison of available soil water between IMS and RMS and is used hereafter for soil water comparisons in this paper. The F_{AW} is weighted by IMZ (refer to Eqn. 1) and weighted by root density of maize (Tufekcioglu et al. 1999) to obtain a field average F_{AW}. Values of F_{AW} range from 0 at the wilting point (θ_{WP}) to 1 at field capacity (θ_{FC}), though values over 1 are possible for short periods if θ is between saturation and field capacity.

$$F_{AW} = (\theta\text{-}\theta_{WP})/(\theta_{FC}\text{-}\theta_{WP}) \tag{2}$$

2.5 Development stages

The dates of specific development stages of maize were determined from records collected during regular field observations of growth throughout the available years of the CSP. There was usually a slight variation in a development stage within a field, so the date listed for a particular development stage of maize is a date when approximately 50 percent of the field was at that stage.

2.6 Calculation of SPI and SPEI

Since precipitation is generally not normally distributed, it is necessary to apply a transformation to the probability of observed precipitation for a set time period (i.e., 1-month, 3-months, etc…) to obtain a normalized index. A three-parameter Pearson-Type III distribution was found to be the best universal model for calculation of the SPI (Guttman, 1999), although a two-parameter gamma distribution was also shown to yield good results. The cumulative probability distribution is then transformed into a standard normal distribution using an approximate conversion from Abramowitz and Stegun, 1965. The values for the SPI are analogous to the number of standard deviations above or below the mean and generally range from -3.0 to 3.0. For a more thorough description of the SPI calculation, refer to Lloyd-Hughes and Saunders, 2002.

The SPEI (Vicente-Serrano et al. 2010) is based on the difference (D) between precipitation and ET_p for a period of time, i, as given in Eqn. 3:

$$D_i = P\text{-}ET_p \tag{3}$$

where P is precipitation (mm) and ET_p is the Thornthwaite method for potential ET. Mavromatis, 2007 showed that other methods of ET_p are not necessarily superior when used in calculation of a drought index and the Thornthwaite method requires fewer inputs than other methods, such as Penman-Monteith. Thus, the Thornthwaite method was used for ETp in the calculation of the SPEI in this study.

The process for calculation of the SPEI is slightly more complex than that of the SPI in part because the distribution of D_i is very likely to contain negative values. Thus, a three-parameter distribution is required for the SPEI, whereas a two-parameter gamma distribution can suffice for the SPI. L-moment ratio (Hosking, 1990) diagrams are used for D_i as it allows for the comparison of the empirical frequency of the series with different theoretical distributions. The L-moment ratios are adjusted by a three-parameter log-logistic distribution to obtain a cumulative probability distribution. From there, the calculation of the SPEI follows the steps of the SPI calculation. For further SPEI calculation details, refer to the step-by-step procedure outlined in Vicente-Serrano et al. (2010).

A 1-month and 9-month SPI and SPEI are used for comparison in this study. Both indices were calculated at ten- day intervals beginning with 30 May (DOY 150) and ending with 7 September (DOY 250). The Applied Climate Information System (Hubbard et al. 2004) was used to collect data used for analysis in this paper. Data for the SPI and SPEI come from nearby Lincoln, NE. Data used in the study come from multiple locations in Lincoln, though the majority of the period of record comes from the Lincoln Municipal Airport Automated Surface Observing System (ASOS) station (KNLK), which is 40 km to the southwest. Distance between KLNK and the CSP site(s) is sufficient to explain 90 percent of variation in maximum temperature and just outside the distance to explain 90 percent of variation in precipitation and minimum temperature (Hubbard, 1994).

There are potential flaws with this method and thus do not expect the indices to match conditions at CSP exactly. However, the long period of record from Lincoln captures severe historical droughts (i.e., 1930's and 1950's), which stations closest to Mead do not. Therefore, the 2003 drought is put in a more representative "historical" context when using data from Lincoln, even if the distance from Lincoln to the CSP sites is too far to match the maximum possible variation in meteorological data. Thus, we believe the sites are close enough such that normalized indices calculated from Lincoln are sufficient for approximating the same indices over the CSP.

3.0 Results and Discussion

3.1 Field Management and weather conditions

Table 1 shows details about crop management, cultivars, final grain yield, and dates of planting, harvest, reproductive stage entry, and beginning of physiological maturity at IMS and RMS in years where maize was the common crop. The planting density at RMS under maize was about 75 percent of IMS, with an average of 62,069 plants/ha over the four years compared to an average planting density for 81,937 plants/ha for IMS. In 2003, planting densities were 84,329 and 64,292 plants/ha at IMS and RMS respectively. Maize was planted on 13-14 May at both sites in 2003.

Site/Year	Crop/cultivar	Plant Pop. (plants/ha)	Planting Date	R1 Date	PM Date	Harvest Date	Grain Yield (Mg/ha)
IMS							
2003	M/Pioneer 33B51	84,329	14-May	25-Jul	12-Sep	14-Oct	14.0
2005	M/Pioneer 33B51	83,200	2-May	14-Jul	14-Sep	18-Oct	13.2
2007	M/Pioneer 31N28	78,708	1-May	17-Jul	16-Sep	6-Nov	13.2
2009	M/Pioneer 32N72	81,509	21-Apr	21-Jul	29-Sep	10-Nov	14.2
RMS							
2003	M/Pioneer 33B51	64,292	13-May	23-Jul	4-Sep	16-Oct	7.7
2005	M/Pioneer 33G66	60,117	2-May	18-Jul	16-Sep	18-Oct	9.1
2007	M/Pioneer 33H26X	62,090	1-May	13-Jul	8-Sep	1-Nov	10.2
2009	M/Pioneer 33T57	61,777	22-Apr	16-Jul	14-Sep	11-Nov	12.0

Table 1: Maize cultivars and planting, harvest, and growth stage dates by season. Yields are adjusted to 15 percent moisture.

The 2003 growing season began with relatively wet conditions as 146 mm of precipitation fell at RMS in the 30 days prior to planting (Table 2). Precipitation over 1 mm occurred on 16 days between planting and the first week of July, with precipitation over 15 mm occurring four times in that period. However, after receiving 31 mm in a five day period from 5 July to 9 July, a long period with minimal or no precipitation was observed at RMS. Between 10 July and 18 August, only 10 mm of precipitation was observed at RMS. Precipitation totaled only 446 mm and 439 at IMS and RMS respectively during the season. The lack of precipitation, particularly during the critical reproductive stage, led to frequent irrigation applications at IMS, with a total of 344 mm applied throughout the season (Table 2). Significant precipitation returned after maize at RMS had reached maturity but minimal precipitation in the critical stages of maize contributed to the significant reductions in yield at RMS.

Time period:	RMS Precip (mm)	IMS Irrigation (mm)	IMS Total (mm)
30 d before planting	146	0	133
Planting to R1	138	108	252
R1 to PM	40	212	269
PM to Harvest	115	24	136
Total	439	344	790

Table 2: Precipitation (IMS, RMS) and irrigation (IMS) between maize stages

The long dry spell was also accompanied by 12 days of maximum temperatures (T_{max}) ≥ 35°C at RMS. Temperatures over 35°C can be detrimental to maize development and reduce yield (Neild and Newman, 1990), particularly when those temperatures are concurrent with water stress in the first few weeks after silking. Most of the days with T_{max} ≥ 35°C occurred during the week of silking onset and again in the period from 16 August to 26 August. The latter period of heat corresponded to the late dough-early dent stage for maize at RMS. The season's highest temperature of 38°C was reported on both 18 August and 25 August respectively. Vapor pressure deficits (VPD) were also higher during this period and indicative of flash drought conditions, with averages of 1.17 and 1.20 kPa in July and August 2003 compared to the 8-year averages of 0.98 and 0.76 kPa for July and August respectively. Cooler temperatures returned to the area at the end of August in 2003 and the first freeze was reported on 29 September, more than two weeks after maize reached maturity. Thus, final grain yields were not adversely affected by an early freeze in 2003.

A holistic view of the 2003 growing season shows that the four phases described in Illston et al. (2004) accurately describe the May-October 2003 time series of soil moisture data used in this study. There was a **moist phase** from early May to 25 June, a **drying phase** from 26 June to 1 August, a **stressed phase** from 1 August to 10 September, and a **recharge phase** for the remainder of the season (Fig. 1). The drying (recharge) date was selected as the date when a clear downward (upward) trend in F_{AW} began at RMS and the stressed phase was chosen as the date when the composite F_{AW} at RMS became less than 0.3. The average FAW and the total precipitation, ET, and GPP for each phase are given in Table 3.

	FAW		ET (mm)		GPP (gC/m^2)		Precip (mm)	
Phase	**IMS**	**RMS**	**IMS**	**RMS**	**IMS**	**RMS**	**RMS**	**IMS**
Moist	0.89	0.85	134	128	130	142	197	
Drying	0.67	0.55	197	176	796	721	44	
Stressed	0.7	0.25	200	133	774	543	76	
Recharge	0.76	0.52	79	50	131	36	73	

Table 3: Average F_{AW}, total precipitation, ET and GPP by phase at IMS and RMS.

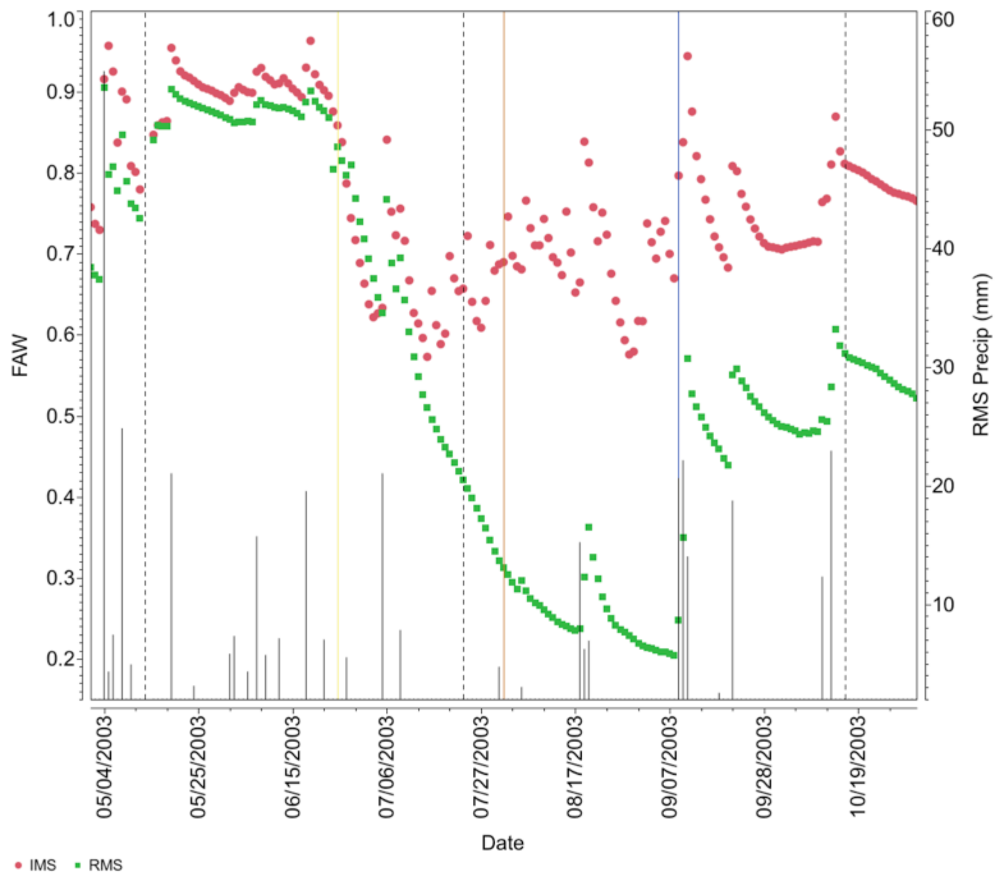

Figure 1: Daily average F_{AW} at IMS (red circles) and RMS (green squares) and total daily precipitation at RMS (black needles). Dashed vertical lines indicate the planting, silking, and harvest dates at RMS respectively. The inception of the drying, stressed, and recharge phases are indicated by the yellow, orange, and blue vertical lines respectively.

Figure 2 shows that the drying phase at RMS was initially only limited to the top two depths (10 cm and 25 cm) and closely mirrored the decline in soil water at IMS. Soil water at 50 cm for IMS and RMS initially was somewhat lower than the other depths, due most likely to a lack of full soil recharge in the previous cold season. Nevertheless, the F_{AW} at 50 cm also began to decline by the middle of the drying phase, albeit at a more accelerated rate at RMS than at IMS, where irrigation treatments prevented further decline. By the end of the drying phase, soil water at 100 cm had begun to be depleted at RMS and was significant by the commencement of the stressed phase. Thus, a great divergence in F_{AW} between RMS and IMS at all four depths was evident by the end of the drying phase and this difference in soil water availability led to stark differences in ET and GPP accumulation (Fig. 3) and eventually in grain yield (Suyker and Verma, 2008; Suyker and Verma, 2009; Suyker and Verma, 2012). The difference in ET rates caused by water stress is illustrated further by the ratio of RMS ET to IMS ET in Figure 4. The ratio started decreasing slightly when F_{AW} at RMS fell to 0.5 and continued to decrease at this rate until F_{AW} was 0.3. The daily rates of ET at RMS relative to the well-watered IMS became very significant once F_{AW} fell below 0.3, which resembles the soil water-ET relationship reported in Waring and Running (1998).

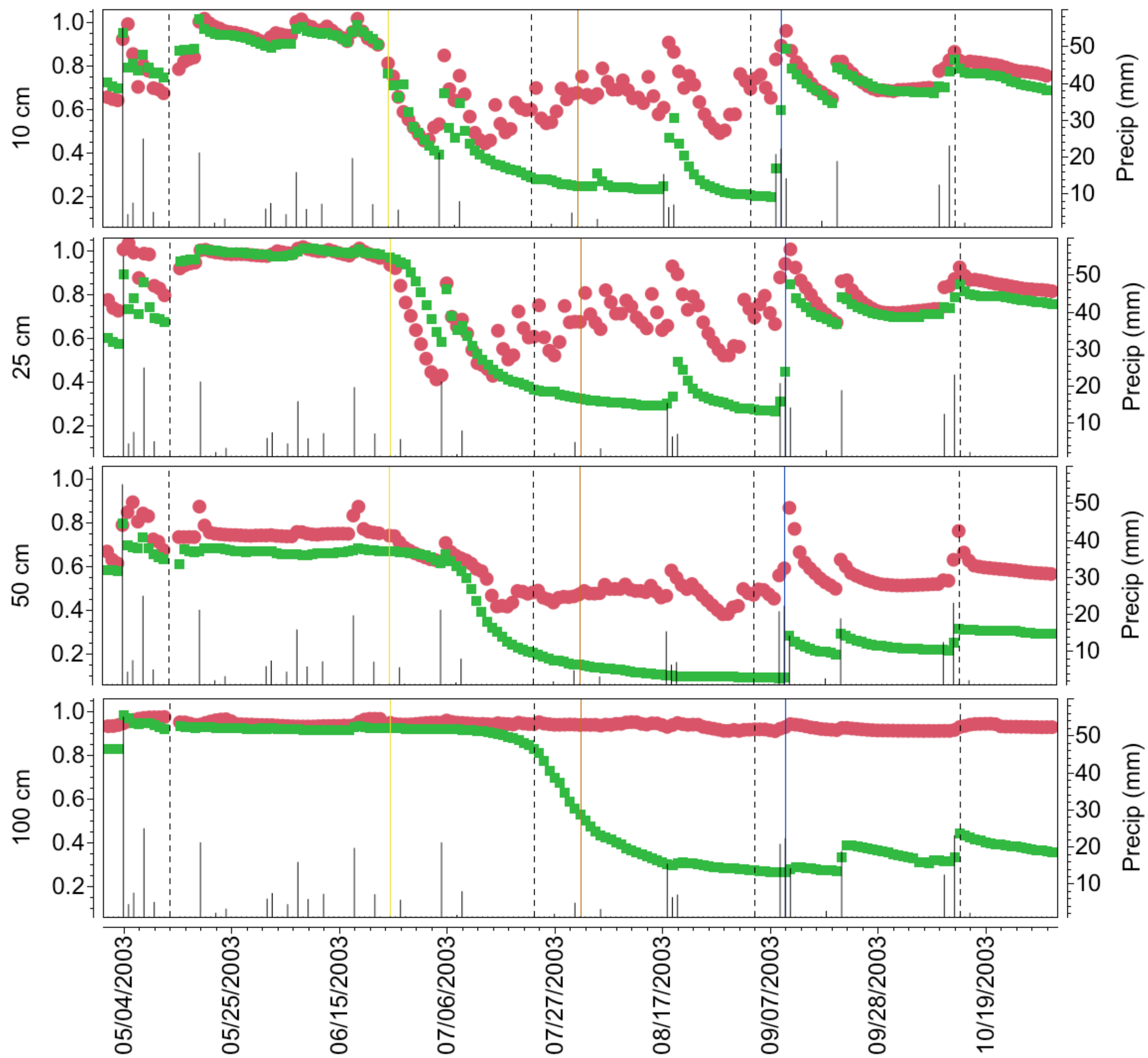

Figure 2: From top to bottom, daily average F_{AW} at IMS (red) and RMS (green) at 10 cm, 25 cm, 50 cm, and 100 cm respectively. Total daily precipitation at RMS is indicated black needles. Dashed vertical lines indicate the planting, silking, and harvest dates at RMS respectively. The inception of the drying, stressed, and recharge phases are indicated by the yellow, orange, and blue vertical lines respectively.

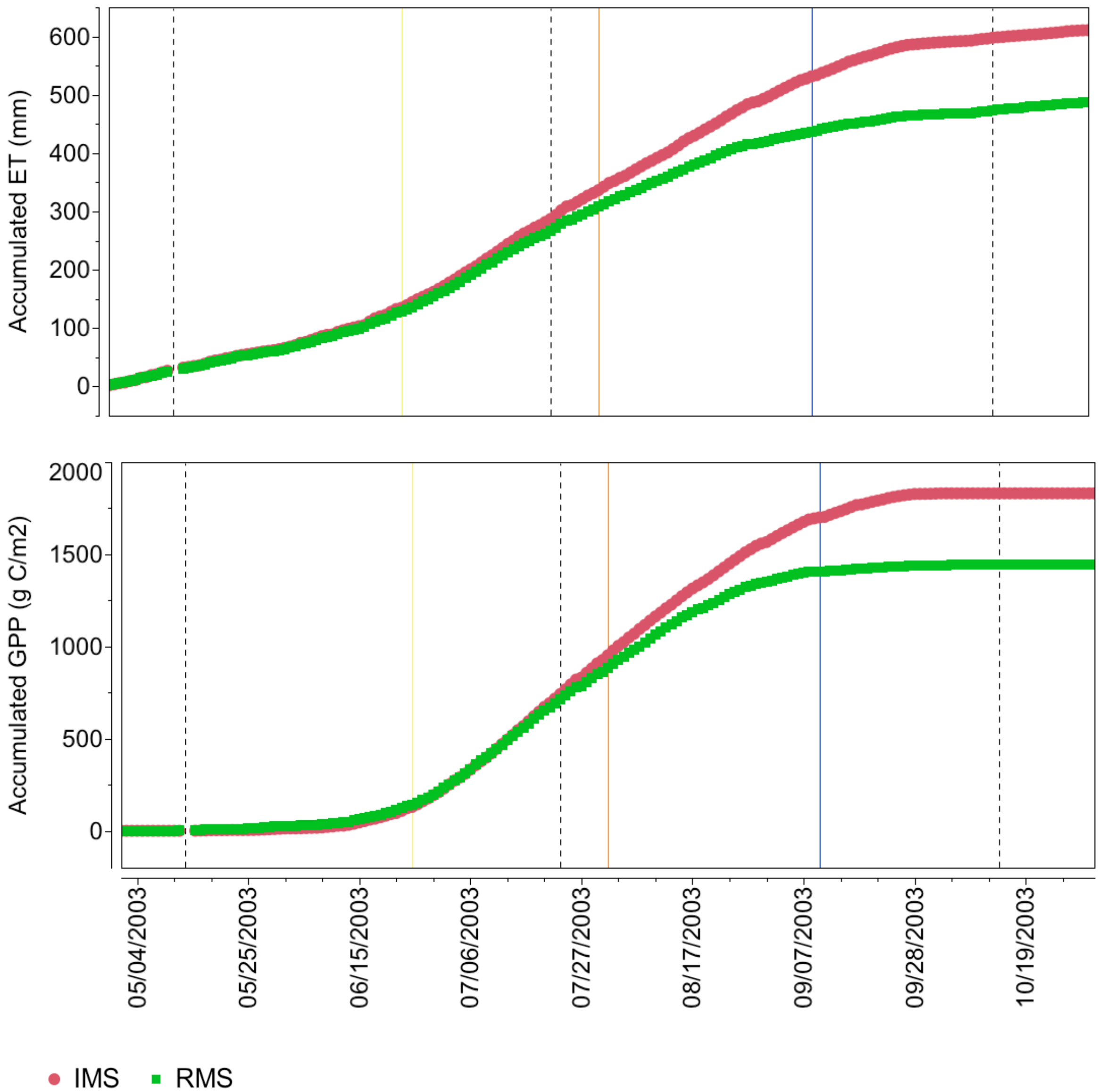

Figure 3: Accumulated evapotranspiration (top) and gross primary productivity at IMS (red) and RMS (green). Dashed vertical lines indicate the planting, silking, and harvest dates at RMS respectively. The inception of the drying, stressed, and recharge phases are indicated by the yellow, orange, and blue vertical lines respectively.

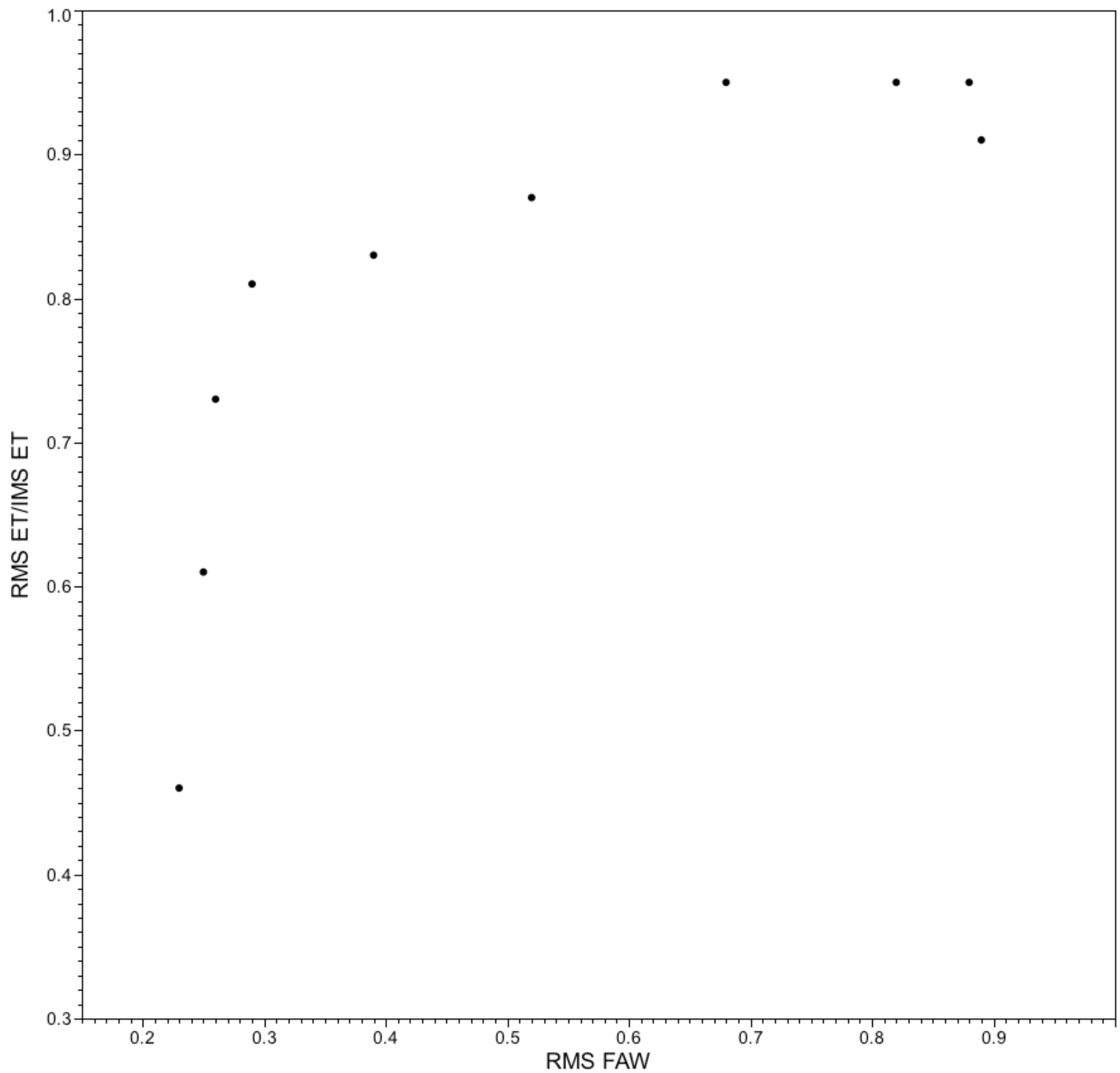

Figure 4: Ratio of total evapotranspiration at IMS to RMS versus the F_{AW} at RMS over ten day periods during the growing season.

The 1-month standardized drought indices (SPI and SPEI) closely matched conditions on the ground in Mead with the SPI and SPEI going from 1.13 and 1.22 respectively on 29 June to -1.78 and -1.43 respectively on 29 July (Fig. 5). Conversely, the 3-month and 9-month indices fell much more slowly during the drying phase and were significantly higher than the 1-month indices by 29 July (Fig. 5). For example, while the 1-month SPI (SPEI) had fallen to -1.78 (-1.43) on 29 July, the 3-month SPI had only dropped to 0.06 (0.19). The 9-month SPI and SPEI were somewhat more indicative of the drying phase by 29 July, but that was as much a result of dry conditions early in the 9-month period than the drought that had developed in the preceding weeks.

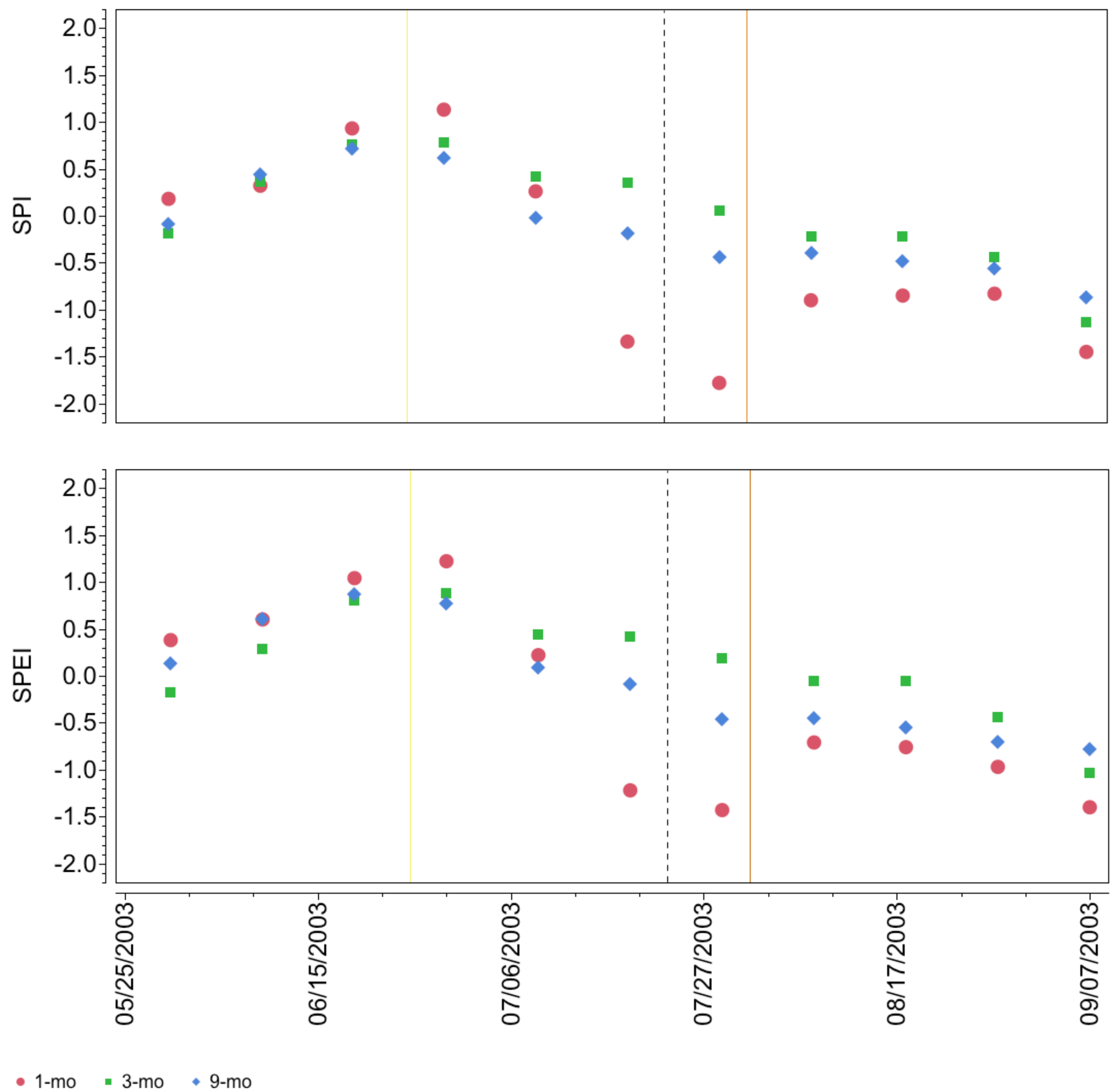

Figure 5: 1-mo, 3-mo, and 9-mo SPI (SPEI) on top (bottom). The dashed vertical line indicates the silking date and the yellow and orange lines indicate the inception of the drying and stressed phases respectively.

The 1-month SPI and the 1-month SPEI increased during the stressed phase and were at -0.9 by 18 August as a result of precipitation, which also corresponded with a brief increase in the F_{AW} at RMS (refer to Fig.1 and Fig. 2). However, the magnitude of the increase in the 1-month indices was partly a result of an additional 20 mm of precipitation falling at nearby Lincoln, NE than at RMS in the period from 31 July to 4 August. Therefore, it is likely that the 1-month SPI and SPEI were somewhat underestimating the severity of the dryness during the stressed phase at RMS, which in turn demonstrates the main disadvantage of using a nearby weather station as a proxy for meteorological data when calculating a drought index.

The remainder of this section of the paper is setup to look at the relationship of these parameters (i.e., soil water, ET, GPP) during individual phases in more detail. Since the first three phases coincided with maize being in the vegetative and/or reproductive stages, soil water (both composite and by individual depth), ET accumulation, and GPP accumulation at RMS are compared with IMS. The recharge phase occurred after maize at RMS had reached maturity and thus only soil water comparisons are applicable. The 1-mo and 9-mo drought indices (i.e., SPI and SPEI) are also discussed during the subsections for the individual phases (except the recharge phase).

3.2 Moist phase

Significant precipitation fell over the region about ten days before planting, which led to an increase in F_{AW} at both sites and elimination of the difference in F_{AW} between the two sites at 100 cm (Fig. 6). Adequate precipitation during the rest of the moist phase allowed for a nearly identical F_{AW} at 10, 25, and 100 cm and only slightly higher F_{AW} at IMS than RMS at 50 cm. Equivalent amounts of soil water between the two sites led to nearly identical daily rates of ET, with IMS pulling slightly ahead in accumulated ET by the end of the moist phase (Fig. 7). That is to be expected however, as a higher population density of maize at IMS would lead to a bit more ET than at RMS, all other things being “equal”.

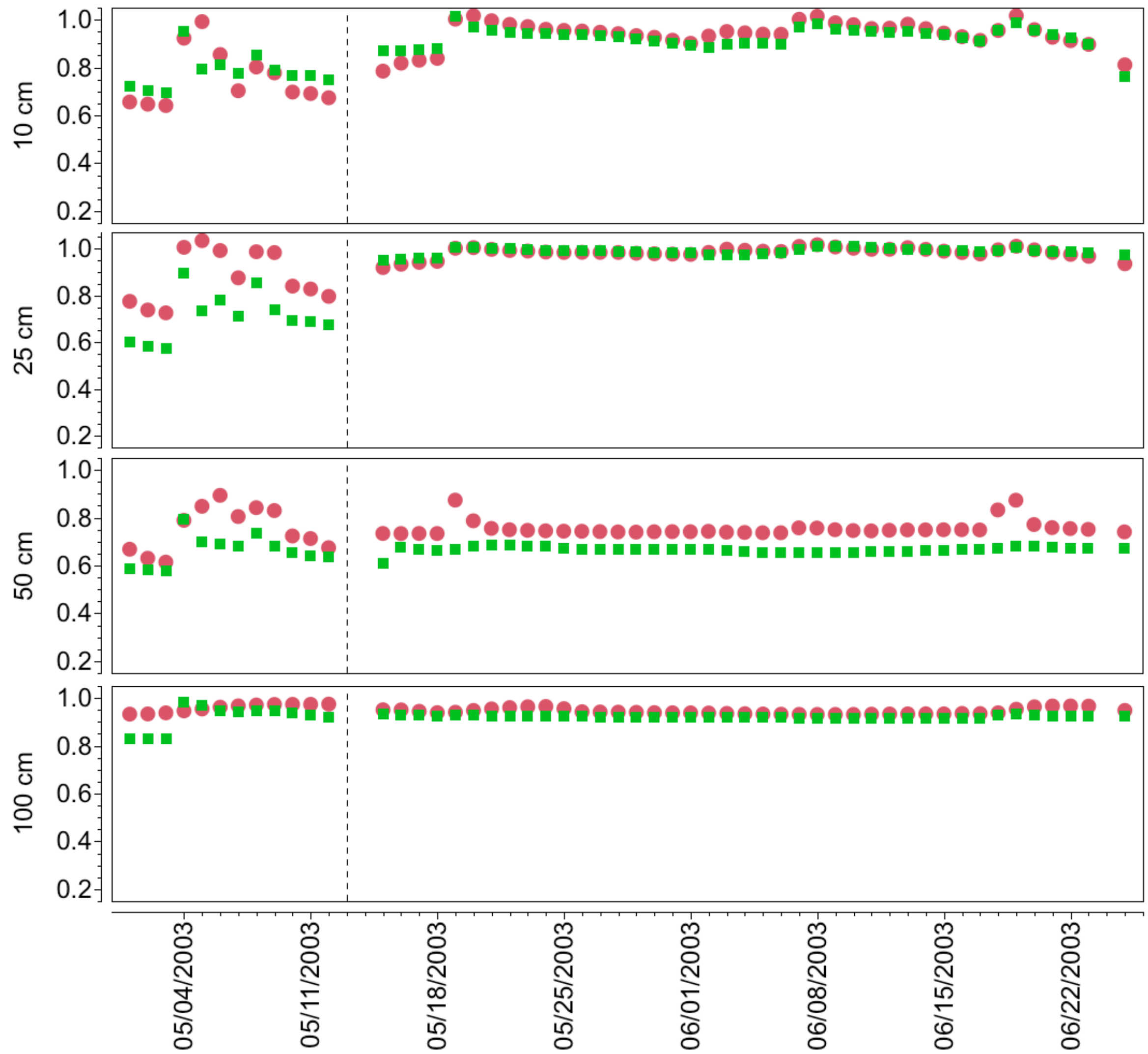

Figure 6: From top to bottom, comparison of fraction of available water (FAW) at 10 cm, 25 cm, 50 cm, and 100 cm respectively at IMS (red circles) and RMS (green squares) during the moist phase. Dashed vertical line indicates planting date of maize at RMS.

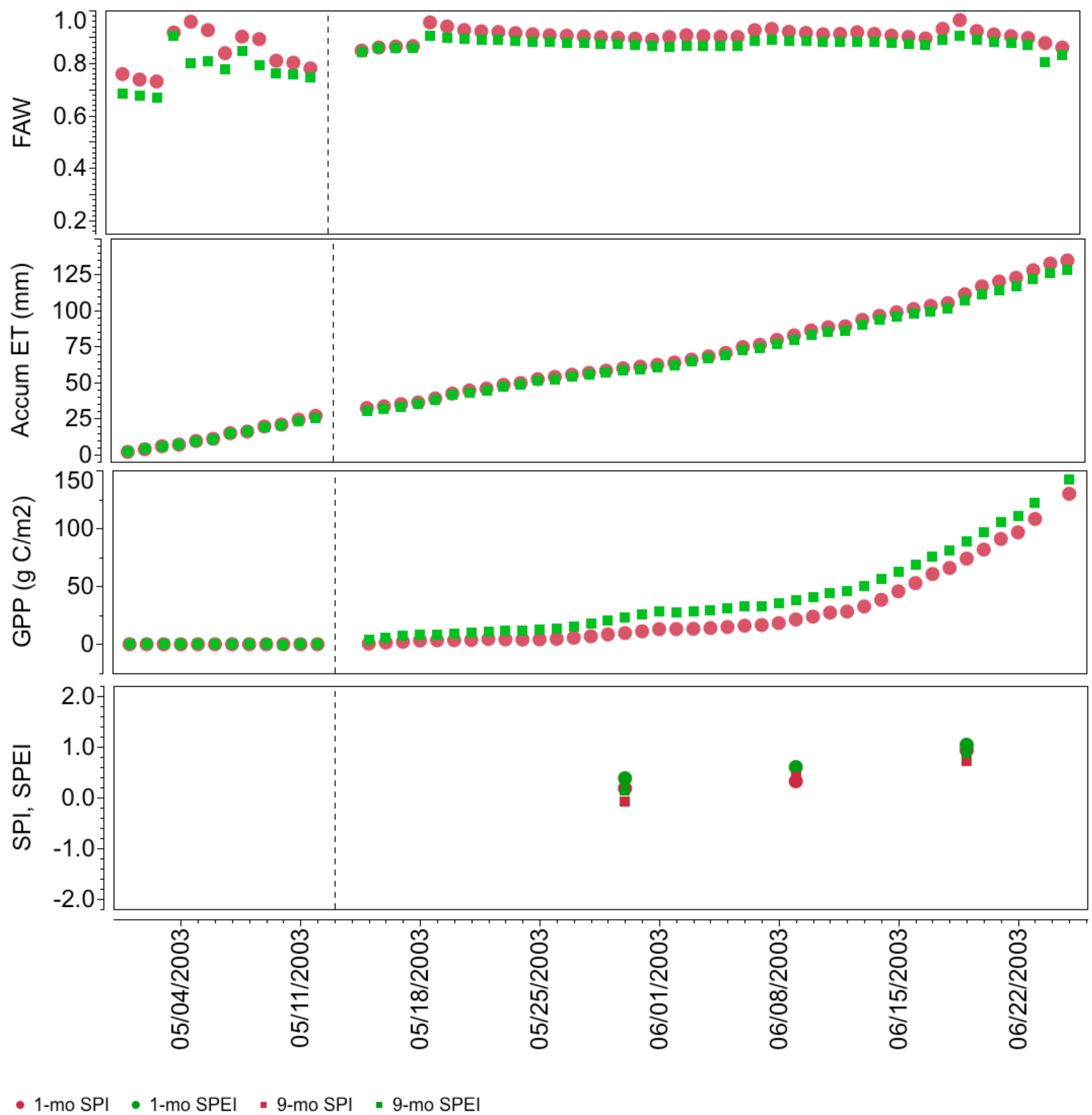

Figure 7: From top to bottom, a comparison of Fraction of Available Water (FAW), accumulated evapotranspiration (ET), accumulated gross primary productivity (GPP) for IMS (red circles) and RMS (green squares), and a 1-month and 9-month SPI and SPEI during the moist phase of the 2003 growing season. Dashed vertical line indicates planting date of maize at RMS.

Figure 7 also shows that GPP accumulation started about ten days after planting and accumulation rates were almost identical between the two sites during the moist phase. Figure 8 further demonstrates that the average hourly rates of GPP during a ten-day period (DOY 171-180) during the moist phase were nearly identical throughout the day. The maize crop was entering the V6 (six-leaf) stage at the beginning of the aforementioned 10-day period so rates of GPP accumulation were lower than later in the season, particularly at IMS. The 1-month and 9-month SPI and SPEI had similar values throughout the moist phase and were responsive to the moist and relatively cool conditions. The 1-month (9-month) SPI and SPEI were at 1.13 and 1.22 (0.62 and 0.77) respectively by late June.

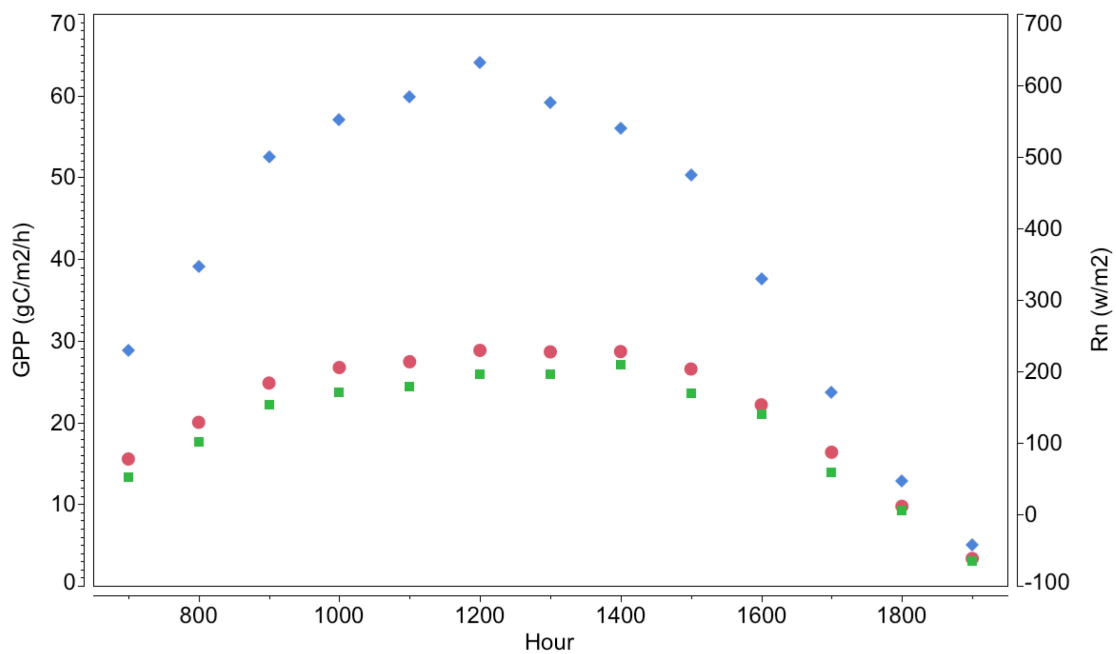

Figure 8: Average hourly GPP (left y-axis) at IMS (red circles) and RMS (green squares) compared to the median hourly net radiation over a ten-day period (DOY

171-180) during the moist phase. Time shown on the x-axis is central standard time (CST).

3.3 Drying Phase

A period of dry weather in late June lowered the F_{AW} at both sites to around 0.60 and thus commenced the drying phase. The F_{AW} returned to 0.86 and 0.80 at IMS and RMS respectively after 21 mm of precipitation on 5 July, but the recharge was very short-lived. The extended period of dry weather combined with a high crop water demand quickly depleted the soil water at RMS and caused irrigation treatments to be applied at IMS every five to six days for the rest of the drying phase. The F_{AW} at 25 cm at IMS was initially lower than at RMS, which could be attributed to a higher plant population density leading to greater soil water demand at IMS than at RMS.

Figure 9 shows that the irrigation treatments at IMS led to the (approximate) five-day moistening-drying cycle at 10 cm and 25 cm and the prevention of large soil water depletion at the deeper depths, particularly after mid-July. By the end of the drying phase, F_{AW} at RMS was 0.42, 0.35, 0.31, and 0.38 less than the corresponding F_{AW} at 10, 25, 50, and 100 cm respectively.

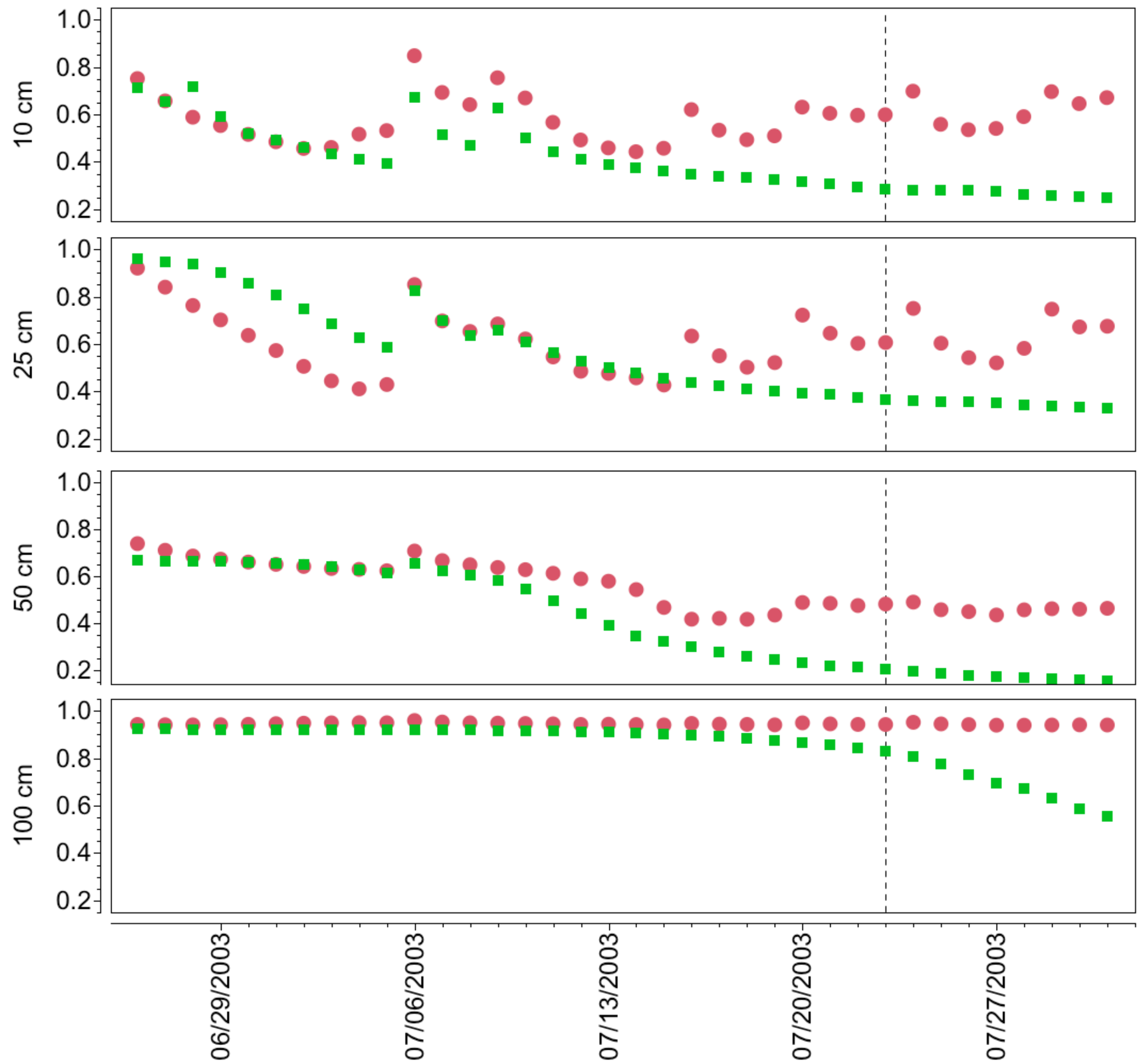

Figure 9: From top to bottom, comparison of fraction of available water (FAW) at 10 cm, 25 cm, 50 cm, and 100 cm respectively at IMS (red circles) and RMS (green squares) during the drying phase. Dashed vertical line indicates silking date of maize at RMS.

The reduction in soil water led to lower daily rates of ET and accumulated GPP at RMS compared to IMS (Fig. 10). The reduction in ET at RMS was less significant at first and the difference between RMS and IMS was less than 1.0 mm/day, such that the difference in accumulated ET between IMS and RMS increased from 6 mm to 27 mm between the beginning and end of the drying phase. GPP accumulation was also affected by the decline in soil water at RMS, going from 10 $gC/m^2/h$ greater than IMS at the beginning of the drying phase to 63 $gC/m^2/h$ less than IMS by the end of the drying phase.

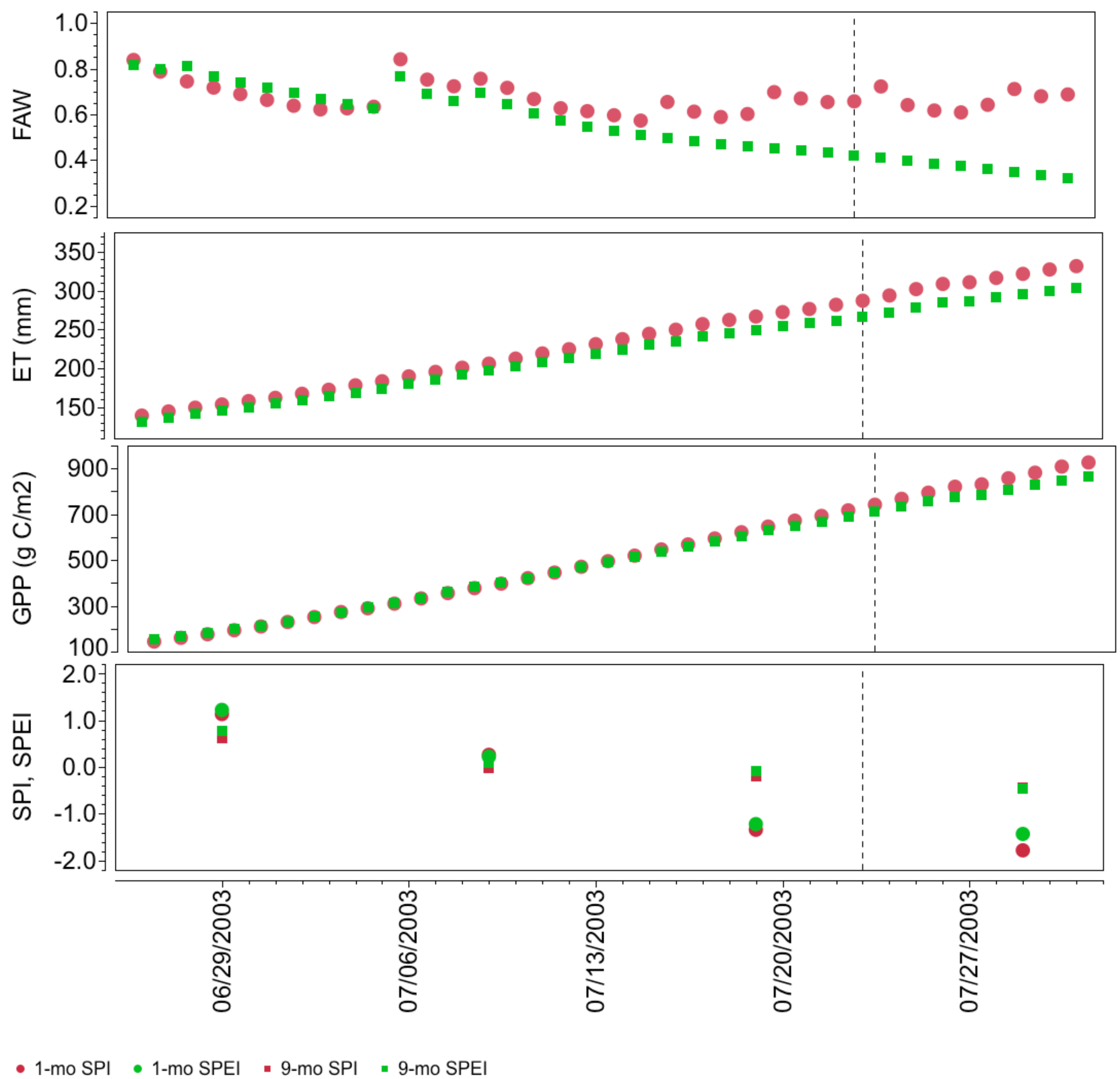

Figure 10: From top to bottom, a comparison of Fraction of Available Water (FAW), accumulated evapotranspiration (ET), accumulated gross primary productivity (GPP) at IMS (red circles) and RMS (green squares), and a 1-month and 9-month SPI and SPEI during the drying phase of the 2003 growing season. Dashed vertical line indicates silking date of maize at RMS.

Plants under water stress close stomata as a direct signal from the metabolic activity of roots under water stress (Schulze 1986). Thus, the reduction in ET and GPP at RMS implies stomatal conductance of maize at RMS was reduced compared to that of maize at IMS. Figure 11 adds validation to this by showing the divergence in average hourly GPP at RMS compared to that of IMS during peak hours of peak net radiation over a ten-day period (DOY 201-210) in the drying phase. For example, during the hour ending at 1100 LST, the average GPP accumulations at IMS and RMS were 67 and 51 $gC/m^2/h$ respectively. Maize was entering the reproductive stage at both sites during this period and thus, hourly GPP accumulation was much more significant than during the ten-day period in the moist phase.

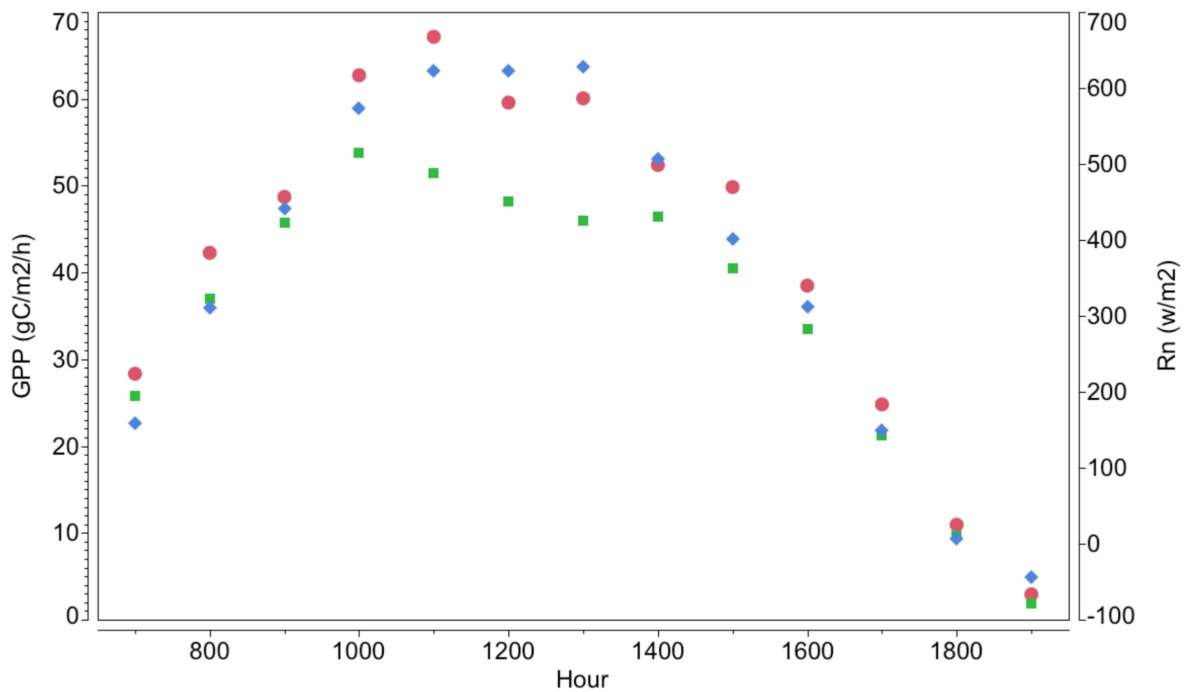

Figure 11: Average hourly GPP (left y-axis) at IMS (red circles) and RMS (green squares) compared to the median hourly net radiation over a ten-day period (DOY 201-210) during the drying phase. Time shown on the x-axis is central standard time (CST).

Both the 1-month SPI and SPEI were extremely responsive to the dry spell, dropping from 1.13 and 1.22 respectively to -1.78 and -1.43 respectively during the five weeks of the drying phase. The 9-month SPI and SPEI slowly declined from 0.62 and 0.77 to -0.44 and -0.46 respectively. Thus, the shorter-term drought indices proved to be quite responsive to the onset of the dry spell during the drying phase. It was originally thought that the SPEI would be more negative but a closer look at temperatures during the drying phase showed that there were enough cooler days mixed in with days of maximum temperatures over 35°C to keep temperatures close to the long-term average of around 25°C during the period.

3.4 Stressed Phase

The stressed phase began on 1 August when F_{AW} at RMS dropped below 0.30. Figure 12 shows that with the exception of a temporary increase (and quick subsequent decrease) in F_{AW} at 10 cm and 25 cm following precipitation on 18-20 August, F_{AW} at 10 cm, 25 cm, and 50 cm declined very slowly or held steady during the stressed phase. This implies that nearly all soil water taken up by maize at RMS was coming from below 50 cm. Indeed, the RMS F_{AW} at 100 cm continued to decline steadily during the first few weeks of August before leveling out at approximately 0.27 for the remainder of the stressed phase. Frequent irrigation treatments at IMS kept FAW above 0.6 at 10 cm and 25 cm, around 0.5 at 50 cm, and close field capacity at 100 cm during this phase. Thus, water stress was not a factor at IMS and the stressed phase ended on 10 September when significant precipitation increased the F_{AW} at RMS to over 0.30.

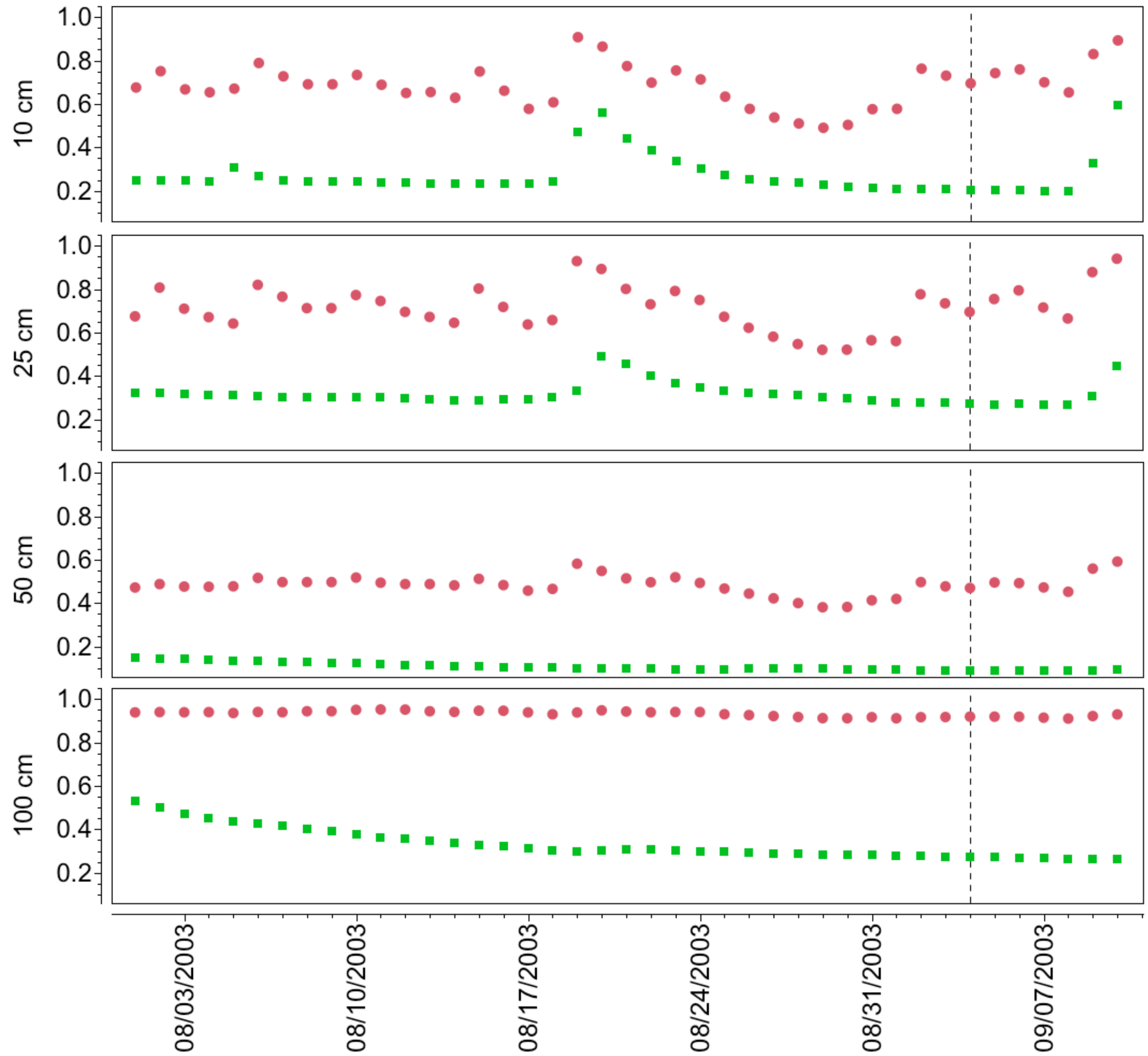

Figure 12: From top to bottom, comparison of fraction of available water (FAW) at 10 cm, 25 cm, 50 cm, and 100 cm respectively at IMS (red circles) and RMS (green squares) during the stressed phase. Dashed vertical line indicates maturity date of maize at RMS.

As referenced in the discussion of the drying phase, stomatal conductance is reduced during periods of water stress, and this was clear during the stressed phase at RMS. Daily ET rates widened further in the stressed phase as IMS averaged 4.8 mm/day and RMS averaged 3.1 mm/day, such that a difference of 94 mm existed by the end of the stressed phase (Fig. 13). GPP was also greatly affected and the difference in accumulated GPP increased to 294 gC/m^2 between IMS and RMS during the stressed phase. Perhaps the most striking evidence of reduced stomatal conductance comes from Figure 14. At well-watered IMS, the average hourly accumulation over a ten-day period (DOY 221-230) closely follows the net radiation curve and peaks at 1100 CST at 62 gC/m^2, indicating that little to no stress was put on the crop (i.e., little to no inhibition on photosynthesis). Meanwhile at the water-stressed RMS, hourly GPP accumulation began to level out early in the morning and peaked at 46 gC/m^2 at 1100 CST, adding more evidence of water stress significantly reducing stomatal conductance.

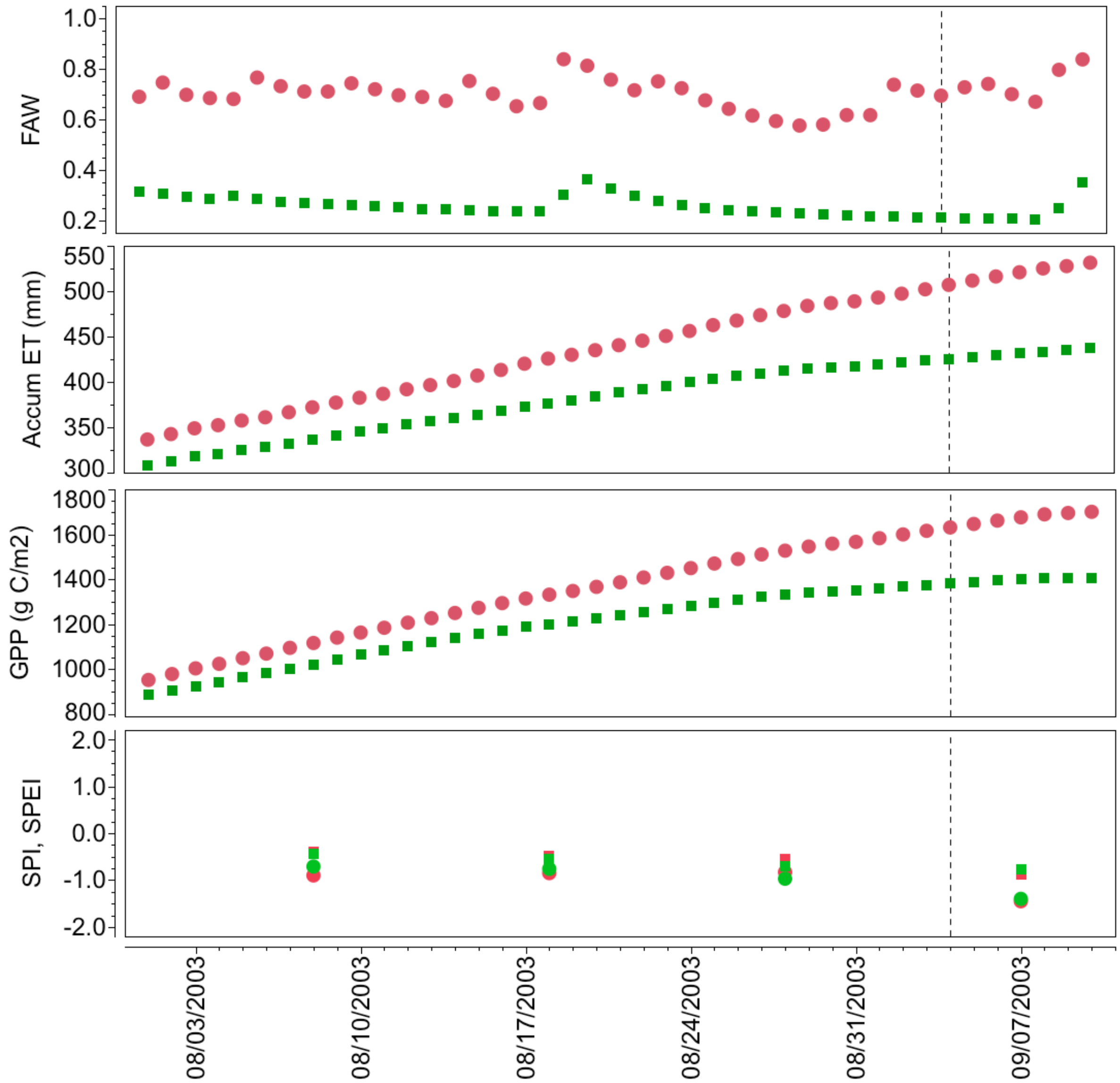

Figure 13: From top to bottom, a comparison of Fraction of Available Water (FAW), accumulated evapotranspiration (ET), accumulated gross primary productivity (GPP) for IMS (red circles) and RMS (green squares), and a 1-month and 9-month SPI and SPEI during the stressed phase of the 2003 growing season. Dashed vertical line indicates maturity date of maize at RMS.

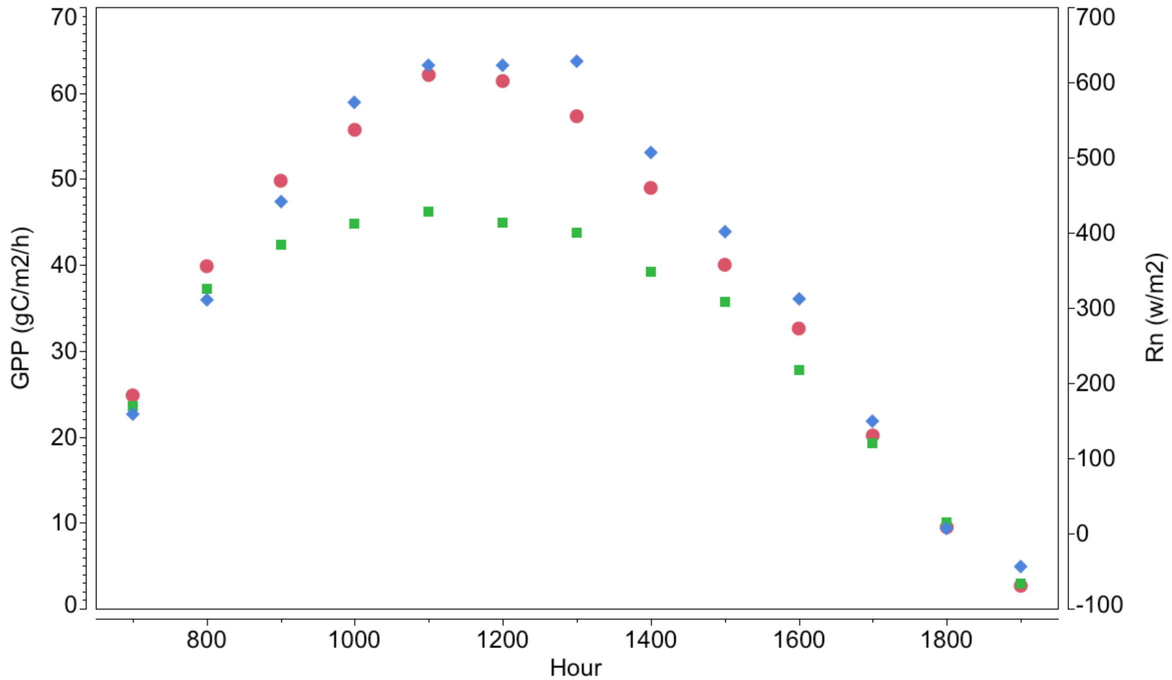

Figure 14: Average hourly GPP (left y-axis) at IMS (red circles) and RMS (green squares) compared to the median hourly net radiation over a ten-day period (DOY 221-230) during the stressed phase. Time shown on the x-axis is central standard time (CST).

The 1-month SPI and SPEI did not match conditions on the ground as well in the stressed phase as they did in the drying phase. This was due mostly to an additional 18 mm that fell at the Lincoln site compared to Mead on 31 July that temporarily brought the one-month indices above -1.0. The brief rise was short-lived though and both of the 1-month indices captured the subsequent decline in soil water at RMS during a period of twenty consecutive days without precipitation that began on 21 August. The 1-month SPI and 1-month SPEI declined below -1.4

shortly after the onset of physiological maturity (4 September; DOY 247) and the 9-month SPI and SPEI declined steadily over the last month of the stressed phase to -0.87 and -0.78 respectively. Therefore, the 9-month SPI and SPEI were somewhat more indicative of the flash drought by the end of the stressed phase than they had been at the end of the drying phase.

3.5 Recharge phase

Significant precipitation did return to Mead as 56 mm fell over a three-day period from 9 to 11 September. It was too late to rejuvenate the maize at RMS unfortunately as physiological maturity had been achieved days earlier. However, Figure 15 shows that the precipitation from 9-11 September brought the 10 cm F_{AW} at IMS to near field capacity and the F_{AW} at RMS to 0.87. Significant recharge also occurred at 25 cm as field capacity was realized at IMS and the F_{AW} at RMS increased to 0.85. Some recharge also occurred at 50 cm, though there was still a very large difference in F_{AW} between IMS and RMS.

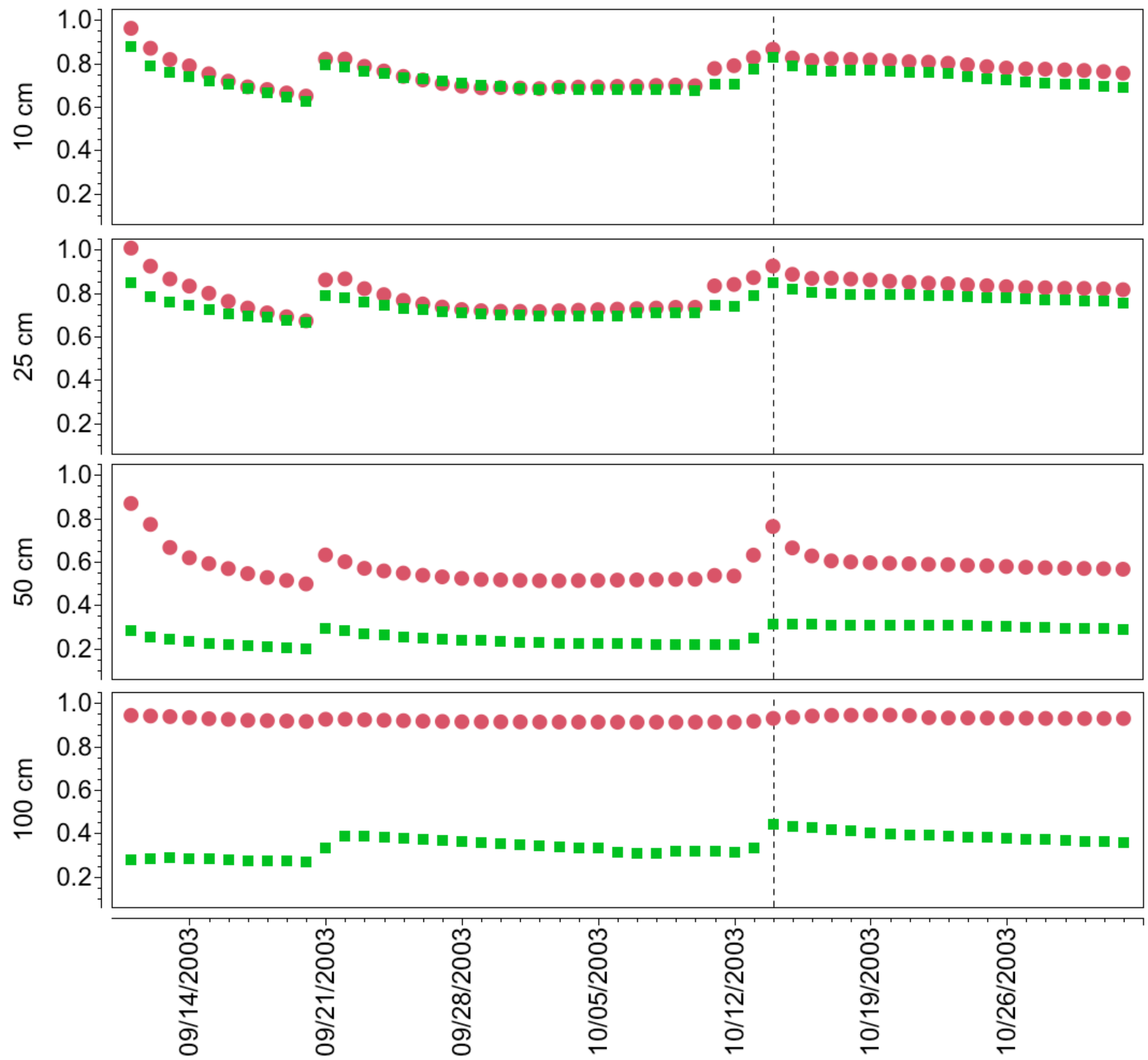

Figure 15: From top to bottom, comparison of fraction of available water (FAW) at 10 cm, 25 cm, 50 cm, and 100 cm respectively at IMS (red circles) and RMS (green squares) during the recharge phase. Dashed vertical line indicates date of maize harvest at RMS.

The remainder of the recharge phase was not exceptionally wet, as only 59 mm fell between 11 September and 1 November. But, the combination of maturing crops and cooler temperatures led to a low demand for soil water (i.e., precipitation at RMS was greater than ET) and this was sufficient to keep 10 cm and 25 cm moist at both sites. It also permitted some additional recharge at 50 cm at both IMS and RMS and at 100 cm at RMS. Perhaps the most interesting aspect of Figure 15 is how the time series of F_{AW} at 10 cm and 25 cm in the recharge phase resembles that of the moist phase, as the difference in F_{AW} was minimal between IMS and RMS. Conversely, the time series of F_{AW} at 50 cm and 100 cm more closely resembles that of the stressed phase, as large differences in F_{AW} between IMS and RMS remained, even with some recharge at RMS. Thus, true recharge only occurred at 10 cm and 25 cm at Mead in 2003, even though there was improvement at the deeper depths.

4.0 Conclusions

The grain yield of 7.7 Mg/ha at RMS in 2003 was only a little more than half of the grain yield at IMS (14.0 Mg/ha). For the sake of comparison, during the more optimal 2009 growing season, RMS had a final grain yield of 12.0 Mg/ha (Table 1). While it is doubtful that the final yield at RMS would have equaled the yield of IMS had the 2003 season remained moist, the yield in 2009 gives a useful comparison for how much yield was potentially lost to the flash drought in 2003. The term flash drought is appropriate for this case study for two key reasons. The first reason is precipitation was adequate and soils were moist for the first two months post-maize planting, which led to comparable rates of ET and GPP accumulation between IMS and RMS during the moist phase of the season. Thus, the initiation of drought was well-defined by actual measurements of precipitation and other agro-meteorological variables.

The second reason is that a prolonged stretch with minimal precipitation occurred during the most critical growth stages for maize and coincided with the drying and stressed phases discussed earlier. It can be implied that the lack of precipitation and decline in soil water at RMS led to corresponding decreases in stomatal conductance, which in turn led to reductions in photosynthesis as evidenced by the significant differences in GPP accumulation, total ET, and final grain yield between RMS and IMS. In contrast, when precipitation was adequate and soil water differences between the two sites were negligible in the moist phase, both sites had nearly identical levels of accumulated ET.

The difference in accumulated ET and GPP between IMS and RMS widened considerably after early August, which closely coincides with the period where soil water at 100 cm went from a linear decrease to a more curvilinear decrease. The timing of the water stress was critical at RMS as the low decline in the ET rate that occurred as maize began silking (23 July; DOY 204) accelerated as maize went through the critical reproductive stage. The irrigated maize at IMS had no discernible water stress and ET rates remained steady throughout the reproductive stage. Significant impacts were therefore realized because of the timing of the drought at RMS. Thus, it can be stated that a flash drought can by characterized by, but not limited to, a well-defined inception with severe impacts on vegetation, including grain crops such as maize, and can be of relatively short duration if a recovery period occurs within a few months of the drought's inception.

This study also confirmed the effectiveness of using a 1-month SPEI and a 1-month SPI for purposes of flash drought detection. Results showed that both 1-month indices were robust at detecting the onset of the flash drought (i.e., in the drying phase) when compared with the 9-month indices as they matched the decline of soil water at RMS very well. The two indices were close throughout the season, indicating that temperatures were close to historical averages over the course of the growing season. While there were indeed several days of temperatures over 35°C in the 2003 growing season, the 2003 season overall was not an excessively hot summer by standards of the western U.S. Corn Belt, and thus the SPEI was not necessarily a better indicator of the flash drought in this study. However, the SPEI yields vital information about the effect of temperature in a drought, and it is likely that the SPEI will be a more robust indicator of drought than the SPI in some future studies. Future work will also be needed to determine if the relationship between indices calculated over different time scales (i.e., 1-month, 9-months, etc…) are similar to what was reported in this study.

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CHAPTER 5: CONCLUSIONS

Eight years of soil moisture and biophysical data from the Carbon Sequestration Project (CSP) provided valuable insights into the inter-relatioship of soil moisture and plant response of corn under varying climatic growing season conditions and the location of these field sites. In addition, the location of these field sites in the transitional zone between the semi-arid High Plains and the wetter sub-humid Corn Belt to the east allowing for the lessons learned from this work to be expand to other parts of these adjacent regions. While it is impossible to totally simulate soil water and biophysical behavior of maize and/or soybeans for another location with data from the CSP sites, the wide range of conditions during the eight-year study period couple with its transitional zone location can give us insight as to the interactions of soil moisture and biophysical variables such as evapotranspiration and gross primary productivity under varying climatic conditions.

For example, the conditions for most of the latter half of the 2003 growing season could be a good proxy for rainfed maize grown under typical conditions of a semi-arid location like the Nebraska panhandle because total precipitation in July and August was less than a typical July and August in Scottsbluff. Conversely, the 2009 season could be a good proxy for a typical season for a maize crop grown in northeast Iowa because of seasonal average temperatures that were more than 2°C below the 30-year average and growing season precipitation that was above average at Mead. The eight-year study period at Mead captured some of the wettest and driest periods of the past 30+ years for this location and therefore, the data shown in this dissertation captures the majority(~95%) of the historical agroclimatological range of temperature and precipitation.

As mentioned numerous times throughout the research chapters, soil moisture is a critical parameter for the Earth's hydrological balance, in part due to its necessity for stomatal conductance to remain high. Soil moisture varied within and between season and none of the seasons in the study period were 100% moist (i.e., no days of stress) or 100% dry (i.e., all days were in stress). However, there was a marked difference in soil moisture between the beginning (2002-2005) and end (2006-2009) of the study period. From 2002-2005, precipitation was consistently below the 30-year median in every growing season and there were prolonged periods of drought stress. Dry spells and subsequent soil water depletion had detrimental impact on yields at the rainfed site (RMS) compared to the irrigated site (IMS), particularly during the 2003 flash drought when the maize yield at RMS was slightly more than half of that at IMS. The climatic growing season conditions during these years demonstrate the benefit of irrigation at a western Corn Belt site like Mead and the necessity of it in a semi-arid environment where seasons are typically like those in the first half of the study period at Mead.

Conversely, precipitation was generally above average over the study sites in the latter part of study period starting after mid-summer in 2006. As documented in earlier chapters, drier spells and soil moisture depletion (particularly at the top soil layer depth) at times during the latter part of the study period, but the magnitude of depletion was lower and the duration much shorter than during the earlier years of the study period. Irrigation water applications were less numerous at IMS and yields at RMS were closer to those of IMS, particularly in 2009 (maize) when there were no days of stress at 50 cm and in 2006 when significant precipitation was well-timed for the soybean production.

One of the goals of the dissertation was to show that timing of precipitation during the growing season (GS) is equally as important as the total precipitation. For example, chapter 3 showed that yield for the maize crop in 2005, which received precipitation well-below the 30-year median that growing, had yields at the rainfed site (RMS) that was only about 1.0 Mg/ha less than in 2007, despite the seasonal precipitation being over 300 mm *lower.* The timing of precipitation was particularly important for irrigation scheduling at IMS. The years with the fewest irrigation application for both maize and soybeans were not the wettest years during the study period. Paradoxically, the year with the fewest irrigation treatments when soybeans were the common crop (2006), had below-average GS precipitation. The year with the most irrigation treatments when soybeans were the common crop (2008) was one of the wettest seasons in the 30-year POR. The difference between the below average 2006 GS and the wet 2008 GS is that precipitation fell at regular intervals during the critical growth period (July and August) for soybeans in 2006 and kept the soil profile moist. In comparison, the only dry spell of the 2008 GS occurred during that same critical period, thus necessitating irrigation applications that prevented depletion of the top half of the soil moisture profile within the root zone of soybeans at IMS.

For years where maize was the common crop, the wettest GS (2007) did not have the highest average soil moisture across all depths or the highest yields at

RMS. That distinction belonged to the 2009 GS, which was only slightly above the 30-year median. Again, timing was the key difference. A large share of the precipitation in the 2007 GS occurred early in the season and then during-late summer and autumn, which are outside of the critical growth stage that determines the yield of maize (i.e., silking during mid-summer). The majority of precipitation in the 2009 GS occurred during the critical stages for maize, keeping the soil profile moist and achieving higher yields than might be expected with total precipitation that was only slightly above the 30-year median. Thus, the old adage that timing is everything, certainly had a strong element of truth in this research when it came to precipitation, soil moisture, and crop yield.

Another goal of the dissertation was to show the direct effect of soil water depletion and soil water recharge on measured biophysical parameters such as ET and GPP. As was expected, total ET and GPP were higher in all seasons at IMS than at RMS over the entire study period. During the dry spells, soil water stress often caused noticeable reductions in the daily rates of ET at RMS compared to IMS, as well as the daily accumulation of GPP and the LE ratio. Collectively, these results imply that soil water stress reduced stomatal conductance, particularly during the afternoon hours when water stress was more incipient. However, if the water stress persisted, as was the case in the 2003 flash drought, the effect was realized earlier in the day.

In chapter 3, the analysis revealed that rainfed maize does have some resilience to soil water deficits if precipitation is timely and sufficient in magnitude for soil water recharge at all depths. Every year that maize was the common crop between RMS and IMS, there was a period when the LE ratio dipped well below 1.0. Also, in every year except 2003, there were significant precipitation events that moistened the soils at all depths analyzed, which in turn led to a significant increase in the LE ratio. Thus, it is possible to conclude that a significant recharge of soil water after incipient water stress can lead to some level of rejuvenation of the maize crop, via increased stomatal conductance. The best example of this was in 2005 when soil water depletion led to a large reduction in the LE ratio by the beginning of the critical period. The LE ratio then increased significantly after a precipitation event about a week after the onset of silking. That rejuvenation did not occur in 2003 because of flash drought conditions, which was studied in depth in chapter 4. The overall goal of it was to compare in situ meteorological data (i.e., temperature and precipitation) and biophysical data (i.e., soil moisture, ET, and GPP) with widely-used drought indices (e.g., SPI) to evaluate effectiveness of the indices to indicate a short-term agricultural drought conditions, which led to severe reductions in yield.

Results in Chapter 4 confirmed the effectiveness of using two 1-month climate indices at characterizing flash drought conditions. The two indices, the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI), are normalized and spatially invariant indices used to determine drought severity. As discussed in chapter 4, the biggest difference between the SPI and the SPEI is the temperature dependence of the SPEI. Thus, a drought combined with well-above average temperatures would be better characterized by the temperature sensitive SPEI more than the precipitation-only SPI.

In the case of the 2003 flash drought, the two indices differed little throughout the season, indicating that temperatures were close to historical averages over the course of the growing season. Thus, there was not conclusive evidence that the more recently developed SPEI was a better indicator of the flash drought with the addition of temperature in the index calculation, as was the original hypothesis. While several days exceeded temperatures over 35°C during the 2003 growing season, the season as whole was not an excessively hot summer, and thus the inclusion of a temperature component in the SPEI did not necessarily make it a better indicator of the flash drought than the precipitation-based SPI. However, if the effects of climate change produce more intense and “hot” droughts, it is likely that temperature could be a more pronounced controlling factor and the SPEI would be a more robust indicator of drought than the SPI.

The primary objective of this dissertation was to show detailed analyses of soil water under crop cover and its relationship with biophysical variables over an eight-year period. While the effect of soil water depletion had been previously well established, the data presented in dissertation are unique in several respects. First, the soil water and biophysical data came from fields (e.g., RMS) that were over 50 ha in size and managed in a way that is typical for producers in the United States Corn Belt. Thus, there is potentially more applicability and/or extensibility of the findings presented earlier in the research chapters for agricultural producers than there would be if the data had come from highly controlled, small experimental plots.

Another unique aspect of the earlier presented data is the location they came from and the duration of the period over which they were collected. The CSP study-sites near the town of Mead, NE are in a true transition zone between rainfed dominant agroecosytems to the east and predominantly irrigated agroecosystems to the west. As discussed in chapter 2, the probability of a high yielding rainfed crop was lower than sites in Iowa and Illinois, but much higher than the other two sites in western Nebraska. Over the eight years used for analysis in the dissertation, the conditions at Mead ranged from wetter than the 30-years average for a site in the Central and Eastern Corn Belt to drier than the 30-year average for a site in the Nebraska panhandle. It could be argued that the wet periods at Mead could be a good proxy for the typical soil water-biophysical variable (e.g., ET) relationship of a maize or soybean crop at a site in the Central and Eastern Corn Belt and the dry periods could be a good proxy for the typical soil water-biophysical variable relationship of a maize or soybean crop in a semi-arid site like western Nebraska. Thus, the Mead CSP site has the potential to be a good “testbed” location for all types of agro-ecological and agro-economic studies and research.

The information presented in the dissertation has the possibility of being of high value beyond producers. One of the recommend areas for future research and work is in the realm of model validation. With land data assimilation systems, such as the North American Land Data Assimilation System (NLDAS) and the Land Information Systems (LIS), becoming more widely used and with land surface models having increasingly sophisticated physics options (e.g., the Noah Multi-Physics model), there will be more demand for validation of outputs like soil moisture and fluxes over well-instrumented sites in a wide variety of ecosystems. The Mead CSP site is a perfect cropland validation site due to its length of record and its unique location in a transition zone between predominantly rainfed and irrigated agroecosystems.

These data assimilation systems also have increasing options for soil moisture assimilation, such as data from the recently launched NASA Soil Moisture Active Passive (SMAP) mission or the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) mission, and from new proximal sensing platforms such as the Cosmic-ray Soil Moisture Observing System (COSMOS). While the depths of soil moisture sensors at the Mead CSP site are a bit too deep for direct comparison, the long period of data from Mead would allow for the development of an observational cumulative distribution function (cdf) that is required when using Ensemble Kalman Filter (EnKF) data assimilation. Thus, it is expected that demand for data from Mead will increase in the coming years. I intend to be a vocal proponent of such projects and hope to be involved in future work with Mead data.